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# FOUNDATIONS OF RADIO

# BOOKS ON RADIO BY

# RUDOLPH L. DUNCAN and CHARLES E. DREW

**Published by**

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# By RUDOLPH L. DUNCAN

## FOUNDATIONS OF RADIO

An introductory text for the beginner. It presents, in a simple and concise manner, the fundamentals of electricity and allied subjects that form the "stepping stones" to a sound knowledge of radio. Symbol tables. Cloth; 5 by 7½ inches.

# OUNDATIONS OF RADIO

BY

RUDOLPH L. DUNCAN

NEW YORK
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1931

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# PREFACE

**Radio** is a highly specialized branch of electrical science, hence radio phenomena are electrical phenomena. The purpose, therefore, of this text is to present, in simple manner, fundamentals of electricity and allied subjects which are "stepping stones" that must be first understood before a comprehensive knowledge of Radio can be expected.

Years of teaching experience have, beyond all questionable doubt, proven to the author that the difficulty students encounter in their efforts to master technical and scientific subjects is met at the very beginning, or elementary stage. It is assuredly impossible to acquire a sound knowledge of Radio until the fundamentals of this subject are mastered.

The instruction contained in this book covers only the elementary theory of electricity and allied subjects that apply to and comprise the essentials of Radio, with no thought of treating the theory and practice of Radio itself.

In order to get the most out of this instruction, Chapter I should be studied in detail after the contents of all subsequent chapters have been learned. This advice is offered because it is usually difficult to grasp the meaning of electrical and radio units from the first reading.

The author desires to express his thanks to the U. S. Bureau of Standards, R.C.A. Radiotron Company, Burgess Battery Company and the Ward Leonard Electric Company for information and illustrations used in the text of this book.

The Author.

May 25, 1931.

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# FOUNDATIONS OF RADIO

## CHAPTER I

## ELECTRICAL UNITS

RADIO AND ELECTRICAL PHENOMENA ARE VERY CLOSELY WOVEN TOGETHER, HENCE THE UNITS OF MEASUREMENT USED IN RADIO WORK ARE BASED ON THE ELECTRICAL UNITS AS GIVEN IN THIS CHAPTER

THE fundamental units of measurement which form the basis of electrical computation are:

(1) *the centimeter*, or unit of length,
(2) *the gram*, or unit of mass,
(3) *the second*, or unit of time.

These three quantities are combined and expressed below in a simple relation known as the centimeter-gram-second, or C.G.S. system.

The C.G.S. unit of *velocity* is the *kine*, representing a distance of one centimeter covered in one second.

1 centimeter = 0.01 meter = 0.3937 inch.

The C.G.S. unit of *force* is the *dyne*, representing the force required to move a mass of one gram one kine per second.

1 gram = 1/28th of an ounce.

The C.G.S. unit of *work* or energy is the *erg*, representing the work accomplished by a force of one dyne working over a distance of one centimeter.

In this chapter are given the definitions of the most important electrical units with simple problems to explain their meanings. These units are met with repeatedly in the study of radio and electricity and, therefore, they should be learned by the student. If these units are learned at the start then no difficulty will be encountered in more advanced work.

## ELECTRICAL UNITS

**The Volt** is the unit of electrical pressure. This pressure is known as the "electromotive force" and, also, as "difference of potential." Electromotive force is abbreviated by the letters (E.M.F.) or (e.m.f.).

> *One volt is defined as the amount of electromotive force necessary to cause a current intensity of one ampere to flow through a circuit having a resistance of one ohm.*

The foregoing definition is the popular and practical one; another and more technical definition states—"the standard volt is $\frac{1}{1.0183}$ of the voltage of a standard Weston cell.'

In electrical practice you will hear references made to this unit by any one of the following names: *Volt, Voltage, Electromotive Force, Pressure or Difference of Potential,* all of which are closely related. The unit volt is denoted by the symbol (*E*).

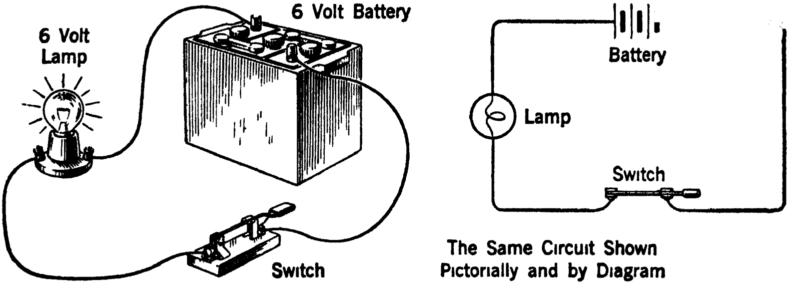


FIG. 1.—A simple electric circuit.

In an electrical circuit we express the amount of the electromotive force as a certain number of volts. To illustrate the proper use of the terms "e.m.f." and "volts" let us consider the simple circuit drawn in Figure 1, where a 6-volt battery is connected to a 6-volt lamp. When speaking about the pressure in this circuit it would be the customary thing to say: "The e.m.f. of 6 volts, applied to this circuit by the battery, forces a certain amount of current through the filament of the lamp, thus causing it to light."

Electrical pressure is analogous to water pressure. To illustrate this let us suppose that a garden hose is connected to a faucet and the valve is opened. Providing there is water supply available in the mains we know that water will run through the hose. The *pressure* in the pipes was necessary in order to get this flow of water. Just how water pressure in pipes is obtained in our homes and buildings should be quite obvious to almost anyone since there are practically only two sources: one source is the result of mechanical work done by a pumping machine of some type; the other is the result of natural gravity provided by a head of water, or water supply originating at some level higher than the outlet where the hose is attached.

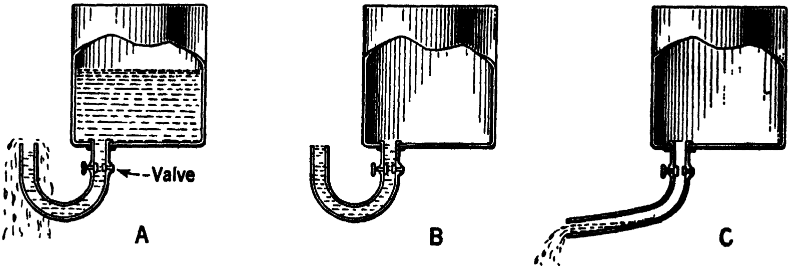


Fig. 2.—Analogous sketches to illustrate that a difference of pressure is required to set up a flow of current in an electrical circuit in a manner quite similar to the difference in pressure level required to cause a flow of water.

To point out the idea that pressure is always essential before a movement or motion of any kind can be produced, we have shown a small tank partly filled with water in sketch *A* of Figure 2. Notice that to the bottom of the tank there has been connected a short pipe, bent into a U shape, the open end of which is arranged exactly level with the tank connection.

The valve acts in a manner similar to a switch in an electrical circuit in controlling the flow. If the valve in the pipe is closed the water pressure is not utilized, although the pressure is always present by reason of the height and volume of water in the tank. But, if we open the valve, the pressure will immediately act, and water will flow through the pipe and gush out at its open end. The flow will continue just so long as there is any water in the tank or any pressure. Finally, when the tank is emptied, it will be seen that the pipe still holds a quantity of water which does not flow out of the open end because both ends of the pipe are level, as shown in sketch *B* of Figure 2. This result shows that, although the water remaining in the pipe has a potential force due to its own weight, it cannot be made use of in this case. Thus we see that it requires a *difference of pressure level* to obtain force by which the water may be made to flow, even though water may be at hand. However, by merely bending the open end downward, as shown in sketch *C*, the water confined in the pipe will begin to flow out, since we have set up a condition where the force due to the weight of water is now acting. The higher the water level in the tank the greater will be the available pressure.

Although we can see the water we cannot see the "pressure." Nevertheless, it is easy to measure water pressure in pounds with a suitable pressure gauge. When we refer to pressure in the electrical sense, we also deal with an unseen force which may be generated in one of several ways. We know how to regulate the intensity of this electrical pressure according to certain requirements, so that it may be applied to a circuit to set up a flow of current. It is also easy to measure electrical pressure by means of a suitable instrument, called a "voltmeter." Several common sources of electrical pressure are batteries, generators, electromagnetic induction and electrostatic induction.

**The Ampere** is the unit of electric current; it represents a certain amount of current flowing at a given rate.

> *One ampere is defined as the intensity (or strength, or value) of the current that will flow through a circuit whose resistance is one ohm, when the applied electromotive force is one volt.*

The following is another definition of the unit of current strength, based on the amount of chemical decomposition taking place in a given period of time, and stated in terms of quantity and rate of flow. "One ampere is that steady flow of electric current which, when passed through a standard solution of nitrate of silver in water, will deposit silver at the rate of 0.001118 gram per second."

The quantity of electricity is measured by the unit "coulomb." Although this unit is defined in a subsequent paragraph let us at this time show the relation between "coulomb" and "ampere" as follows: "When one coulomb of electricity passes a given point in a circuit, every second of time, one ampere of current is said to flow." Hence, if 2 coulombs of electricity pass a given point in a circuit per second the strength of the current is 2 amperes. In a given circuit, therefore, to find the total quantity of electricity expressed in coulombs we must take the product of the current in amperes and the length of time in seconds that the current flows.

Current is denoted by the symbol ($I$) and is measured by an instrument called an "ammeter."

Again refer to the drawing in Figure 2 to be certain that you have a clear understanding of the difference between "quantity" and "rate of flow." Water flowing through a pipe at the rate of a certain number of gallons per minute can be compared to current in amperes passing through a circuit. In a water system "gallons" represents the quantity and "gallons per minute" the total amount for a given time, or rate of flow, whereas, in the electrical circuit, "coulomb" is the quantity and "amperes" is the rate of flow of a given quantity.

An important point to be mentioned in this discussion is that throughout the whole length of the pipe there are oppositions set up which prevent a free movement of the water. These oppositions are due principally to friction by contact of the water with the inner walls of the pipe, bends in the pipe, and the length and size, or cross-section, of the pipe. In any of its forms, opposition must be met and overcome by the pressure before water flows, and, of course, the opposition will govern to some extent the amount of water that flows in a given time under a given pressure. It is easy to see that any opposition presented by the pipe itself will retard the water flow.

This opposition is comparable to that which is present at all times in electrical circuits, because the wires or other metallic parts do not permit a free movement of electrons, or current, but, rather, the current is forced to flow through the materials used to construct the circuit under the applied voltage. Each different kind of metal has its own specific resistance. For instance, current flows more readily through silver than through copper, and more readily through copper than iron. Thus, if we have two circuits consisting of the same length and cross-section of wire, and if one circuit uses copper wire and the other iron wire, and if exactly the same voltage is applied to both circuits, it will be found, under these conditions, that about six times as much current will pass through the copper wire as compared to the iron-wire circuit. This is because the relative resistance of copper is 1.075 as compared to 6.37 for iron. In the case of the electrical circuit this opposition of the material itself, which governs to a large extent the intensity of the current flow, is known as the "resistance." This subject is again discussed under the unit of resistance, the ohm.

**An Ampere-Hour** is the unit in general use in battery-charging service; it represents a continuous flow of current of 1 ampere for 1 hour.

**The Ohm** is the electrical unit of resistance. Resistance is the natural opposition which all materials offer to the flow of electronic current, and since this opposition is inherent in all matter it must be overcome by the electromotive force before current will flow.

> *One ohm is the amount of resistance of an electrical circuit when an electromotive force of one volt is required to force a current of one ampere through it.*

The following is a definition of the unit of resistance based on a physical standard: One ohm is the amount of resistance that would be offered to a steady flow of electric current by a column of mercury of uniform cross-section, 106.3 cm. long, 14.4521 grams in weight at a temperature of 32° F., or 0° C.

> *Note:* One centimeter is a little less than a half inch. One ounce is equal to 28 grams.

The ohm is denoted by the symbol ($R$) and is named after the German scientist, George S. Ohm. He was responsible for recognizing the relation existing between the "voltage," "resistance," and "current" in all electrical circuits and formulating this relation into what is probably the most important and widely used law in electricity, known as **Ohm's Law.**

When a conductor has an exceptionally high resistance we use the unit "megohm." For conductors having a very low resistance we use the "microhm."

One megohm equals 1,000,000 ohms.

One microhm equals 1/1,000,000th of an ohm.

**The Coulomb** is the unit of electrical quantity used to express the total quantity of electric current passing through a circuit in a stated time.

*One coulomb is the quantity of electricity that will flow in a second through a circuit having a resistance of one ohm when the applied e.m.f. is one volt.*

We are now dealing with "quantity" in electricity in about the same way that ordinary standards, a pound or gallon for instance, are used to measure supplies such as sugar, milk, etc. Thus, if we wish to know the number of "coulombs" or "quantity of electricity" passing through a circuit in a given time we must multiply the number of amperes by the number of seconds the current continues to flow.

The following example shows how to apply this rule: Suppose the rate of current flow for a particular circuit is 8 amperes and the current continues to flow steadily for 4 seconds. The total quantity of electricity passed will be 8 × 4, or 32 ampere-seconds, or 32 coulombs of electricity. Also, if 2 amperes flow for 16 seconds we would have 32 ampere-seconds, or 32 coulombs.

The unit "coulomb" is also applied in electrostatics with reference to placing an electrostatic charge in a condenser, and in this usage it is defined as follows: "One coulomb is the quantity of electricity necessary to raise by one volt the difference of potential between the plates of a condenser whose capacitance is one farad."

The coulomb is denoted by the symbol ($Q$).

**The Henry** is the unit of inductance. Inductance is a certain property possessed by every electrical circuit which establishes an electromagnetic field about its conductors and windings (coils). Inductance is also applied to the peculiar property of all conductors and windings (coils) which tend to *oppose* any current change produced by a circuit within itself by virtue of the changing magnetism which is set up whenever current varies or tends to vary in strength. The effect is pronounced in any circuit in which the current is continually changing intensity, as, for example, in a circuit carrying pulsating direct current or alternating current. The net result of inductive effects is the generation of a second e.m.f. separate from the applied e.m.f. which causes the current to flow.

> *A circuit is said to have an inductance of one henry when an electromotive force of one volt will be induced in the circuit by a current varying at the rate of one ampere per second.*

The letter ($L$) is the symbol used to denote inductance.

This property of "inductance" exists in all portions of an active circuit because the electromagnetic lines of force (flux) set up by the current will vary in magnitude according to every change in current intensity, and these magnetic lines are continually acting upon the very wires (or conductors and coils) which comprise the circuit. The term "self-inductance" is commonly used to express this peculiar property exhibited by a circuit due to the action of its own magnetic lines upon itself. The tendency of a circuit to prevent changes in current intensity and spoken of as the "self-inductance" of a circuit, as just mentioned, represents one kind of opposition and it must not be confused with a circuit's "resistance."

Resistance is always present whether the current varies in strength or whether it flows steadily. However, "inductance effects" are not present in a circuit when a steady direct current flows, for in this case the magnetic lines are also steady and consequently do not act upon the conductors.

**The Farad** is the unit of electrical capacity and is abbreviated (fd.). This unit relates to the amount of charge that can be stored up in a condenser in electrostatic form under a given e.m.f. measured in volts.

*A condenser is said to have a capacitance of one farad if the potential difference between its plates will be raised one volt by a charge of one coulomb.*

From this definition we see that a condenser when connected in a circuit and supplied with voltage will store up a definite amount of electricity in static form.

The farad is considerably too large to be applied in practical work. We therefore have two sub-multiples of the unit in common use. They are:

Microfarad (abbreviated mfd. or $\mu$fd.)

Micro-microfarad (abbreviated mmfd. or $\mu\mu$fd.)

One microfarad is equal to one-millionth part of a farad. One micro-microfarad is equal to one-millionth part of a farad again subdivided into a million parts; that is to say, a micro-microfarad is one-millionth of one-millionth part of a farad.

Example.—Either unit, microfarad or micro-microfarad, may be used to express a certain numerical value according to one's own preference. As a rule, values in the order of 1000 mmfd. and higher are expressed in microfarads (mfd.). Here are a few examples of how a value may be written in terms of either unit:

1 mmfd. = 0.000001 mfd.

250 mmfd. = 0.00025 mfd.

1000 mmfd. = 0.001 mfd.

A simple condenser is shown in Figure 3. It consists of a thin piece of suitable insulating material, such as mica, on either side of which is glued a sheet of tinfoil. The tinfoil sheets are called the "plates" and the mica the "dielectric." If two wires are connected from a source of voltage to the respective plates, the e.m.f. thus provided will cause an electrostatic charge to be stored up by the mica. In Figure 4, the dry cell of 1.5 volts causes a difference of potential of 1.5 volts to be set up between plates *A* and *B* of the air-type condenser; the electrostatic lines in this case are stored up in the air, but in Figure 3 they are stored in the mica. The condensers in Figures 3 and 4 are called fixed condensers because no provision is made to alter their capacitances.

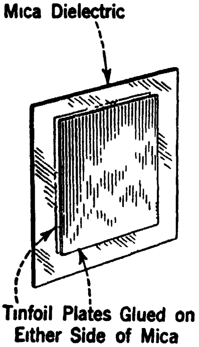


FIG. 3.—The drawing shows that a mica sheet and tinfoil plates form a condenser.

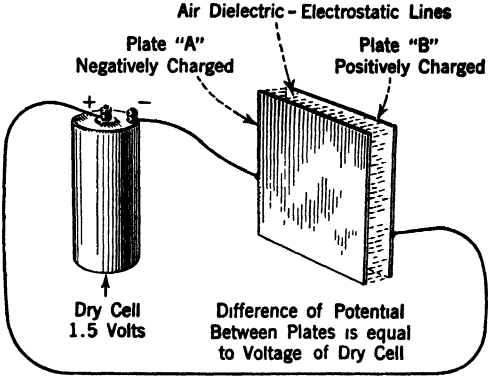

Air Dielectric - Electrostatic Lines
Plate "A" Negatively Charged
Plate "B" Positively Charged
+
−
Dry Cell 1.5 Volts
Difference of Potential Between Plates is equal to Voltage of Dry Cell

FIG. 4.—Illustrating how an electrostatic charge may be stored up in a condenser. The dashed lines between the plates represent the invisible electrostatic lines of force.

The multi-plate variable air-type condenser in Figure 5 consists of a set of fixed and movable plates; this type is in general use in radio work for tuning purposes. The capacitance of this condenser is varied by rotating one set of plates, which acts to change the effective relationship between both sets of plates. The dielectric medium, which possesses the property of setting up electrostatic lines of force in a condenser of this kind, is the *air* which separates the plates. The particular kind of dielectric used, whether it be air, mica, paper, or any other suitable material, has an important bearing upon the amount of charge the condenser will take on. The dielectric material also governs the amount of voltage that can be applied to the condenser without placing the insulating quali-

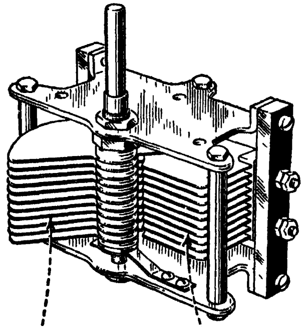


FIG. 5.—One type of multi-plate variable air type condenser.

ties of the dielectric under an excessive strain that would eventually result in a breakdown.

Capacity is designated in all of our writings and formulas by the letter (*C*).

**Electrical Work and Power.**—In radio and electrical subjects we deal considerably with work and power. Through experience we find that very often the terms, *force*, *power*, *energy*, and *work* are not thoroughly understood by everyone. To avoid any confusion among these terms we will explain their meanings in the following paragraphs, also giving a practical example of their use.

There are different kinds of force that will produce work when properly directed. For instance, we apply muscular force whenever we exert ourselves in the performance of certain tasks. Also, we have mechanical force derived from various types of motors and engines which may be operated with compressed air, gas, water, steam, gasoline, and so on. There is also chemical force and electrical force. Other examples of force could be cited, but electromotive force is the force most frequently dealt with in our work. It will be repeatedly mentioned that an electromotive force, when properly applied, will cause or tend to cause a flow of electrical current.

**Force** is an unseen agent which acts to cause some change in the existing motion of a body, or mass, or it may cause a change in direction of motion, or it may in some cases alter the physical shape of the body acted upon.

At this time let us review a few of the possible conditions relating to force. If a body is at rest and force is applied it will tend to set the body in motion; or if the body is already in motion a force may be applied in such a way as to cause the body to accelerate (move faster), or slow down, or perhaps come to a complete stop; or if a body is moving in a certain direction a force applied in some other direction will tend to cause the body to change its original course of direction.

It is to be understood that force does not always produce motion. This is a fact of which you are perfectly aware. For a simple illustration consider what would happen if you pushed against the side of a house with all your strength; you know that the energy expended would not result in the house being moved, regardless of how hard you may have worked to accomplish this purpose. These natural laws are true in the case of electricity; an electromotive force does not in every case act to cause a movement of current, but it tends to do so. Thus, it may be said that a force acting over a distance or through space is a factor of work but the force does not necessarily produce motion.

**The Joule** is the unit of electrical energy or work.

> *One joule represents the amount of work performed, or energy expended, including that consumed in generating heat, when an electromotive force of one volt is applied to a circuit and a current of one ampere flows for one second of time.*

We can express electrical work as the product of the "electromotive force" in volts and the "quantity of current" in coulombs. Now, since an *ampere* is equal to one coulomb of electricity multiplied by a time period of one *second*, then this entire relation can be stated as follows:

ELECTRICAL WORK (JOULES) = VOLTS × AMPERES × SECONDS

The symbol (*J*) is used to denote the joule.

**Work** is performed whenever a force overcomes opposition, or resistance, in causing a body upon which it acts to be set into motion. The amount of work done can be conveniently measured, whether it is the result of mechanical, chemical, electrical, or heat effects. Work, therefore, is done whenever energy is expended. This statement, no doubt, is plainly obvious to everyone and is intended to point out the fact that to do work does not necessarily mean that a weight must be lifted. For instance, work is done by compressed air acting upon a piston in a rivet machine; an explosion of a charge of gasoline vapor acting on one or more pistons provides the power in a gasoline motor for use in boats, automobiles, and so forth; steam engines utilize the expansive force of steam on the heads of large pistons as a source of power. Steam may be used in a plant to drive electric generators which are in turn used to supply light, heat, and power. We could go on indefinitely citing examples of how power is obtained to do different kinds of work.

A simple illustration of mechanical work is a team of horses in action, exerting energy in pulling up a very heavy weight by means of suitably arranged pulleys and lines.

An illustration of electrical work is an electric flatiron connected to a 110-volt house-lighting circuit. The work or energy expended in the electrical case is represented by the heat developed in the coils, called heating element, mounted within the iron. In order for this work to be done successfully we know that the voltage on the line must have been effective in overcoming all the oppositions of the circuit, with the result that a certain value of current was forced through the coils. This teaches us how electrical energy is transferred into heat energy.

The total amount of work done is calculated by multiplying the amount of a force and the distance through which it acts (or is applied) in overcoming resistance, which results finally in a transference of energy from one form to another.

The accomplishment of a certain piece of work is independent of *time*. That is to say, it may require different amounts of time, as for instance a day, a week or perhaps longer, to complete a given work. When the element of time is reckoned along with the work we must make reference to the term *power*.

**Power** is the *time rate* of doing work. It represents both the expenditure of a certain amount of energy and the length of time during which it is maintained. Since the term *power* includes the element of time we must not confuse it with the total amount of work actually performed.

The relation between "power," "work" and "time" can be set down as follows:

$$\text{POWER} = \frac{\text{WORK}}{\text{TIME}}$$

**The Watt** is the unit of electrical power. From a little consideration of the explanations previously given in regard to the joule (or unit of work), and the ampere (or the unit of current), and the volt (or unit of pressure), it is evident that the amount of "power" in any electrical circuit must be a combination of these three factors.

Thus, *one watt is defined as that unit of power equivalent to one joule divided by one second.* This relation may be written as follows:

$$\textsc{Watts} = \frac{\textsc{Joules}}{\textsc{Seconds}}$$

Now we already know that a *joule* is the amount of work resulting when one *ampere* of current is maintained for one *second* under an applied e.m.f. of one *volt.* Therefore, combining this relation into one expression we have the well-known watts formula:

$$\textsc{Watts} = \textsc{Volts} \times \textsc{Amperes}$$

The watts formula expressed immediately above is for a direct-current circuit. The same formula is repeated below but using the electrical symbols.

$$W = E \times I$$

It is clear that if we wish to ascertain the number of watts of power in a direct-current circuit, or in the parts which form the circuit, we have simply to multiply the volts by the amperes.

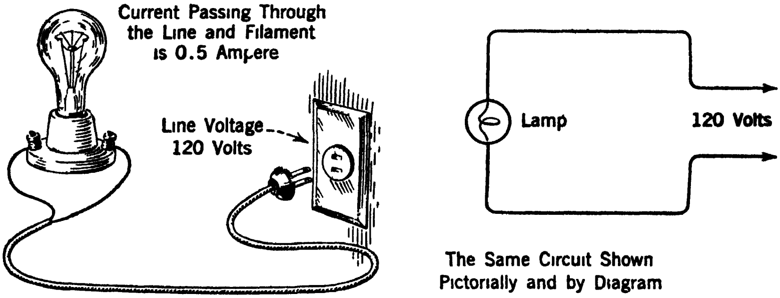

Current Passing Through the Line and Filament is 0.5 Ampere
Line Voltage 120 Volts
Lamp
120 Volts
The Same Circuit Shown Pictorially and by Diagram

Fig. 6—A simple practical circuit The filament of the lamp is heated by current supplied from a power line.

The following definition of a watt should be learned:

*One watt is the power expended when one ampere of current flows steadily through a circuit under a pressure of one volt.*

A practical example is worked out on the next page, showing how to find the wattage of a simple circuit.

**Problem:** Find the number of watts of energy expended in the circuit in Figure 6 when the e.m.f. is 120 volts and the current drawn by the lamp is 0.5 amp.

*Solution:* The wattage for this circuit is computed as follows:

(1) Write the formula: $W = E \times I$
(2) Substitute known values: $W = 120 \times 0.5$
(3) Perform the work as shown at the right:

$$\begin{array}{r} 120 \\ \underline{0.5} \\ 60.0 \end{array}$$

(4) Write the answer: $W = 60$ watts

The number of watts may be expressed in the larger unit "horse-power," abbreviated "H.P." In terms of horse-power, one watt is equal to $\frac{1}{746}$th of an electrical horse-power. This is equivalent to saying that one electrical horse-power equals 746 watts, or

1 ELECTRICAL H.P. = 746 watts

Another unit in common use is the "kilowatt." One kilowatt, abbreviated " kw.", is equal to one thousand watts, or

1 kw. = 1000 watts

**Practical Use of Watts Formula.**—The watts formula, for the law of power, can be stated in three ways as shown below for convenience in working out practical problems. Exactly similar relations are represented between the quantities in each of the formulas. An inspection of these formulas shows that the value of any one of the three quantities may be easily found, providing the other two quantities are known. Using the symbols, we have

$$W = E \times I$$

or

$$I = \frac{W}{E}$$

or

$$E = \frac{W}{I}.$$

Another practical example in the use of the watts formula is worked out on the next page.

Problem: Let the rated power of a circuit be 660 watts and the line voltage 110 volts. What is the value of the current passing through this circuit?

*Solution:* The formula is written first and the computation completed as follows:

(1) Write formula: $I = \frac{W}{E}$

(2) Substitute known values: $I = \frac{660}{110}$

(3) Solving, we have $I = 6$ amperes. *Ans.*

**The Watt-hour and Kilowatt-hour.**—The watt-hour is a convenient unit to use in practical work for denoting the amount of energy expended in a given number of hours.

*One watt-hour is equal to one watt of electrical energy expended in one hour.*

The watt-hour is the unit of measurement that is applied in the calibration of electric meters installed in our homes, factories, office buildings, and so on, for indicating the amount of electricity consumed; the meters used for this purpose are usually equipped with several dials for recording and are called watt-hour meters.

Since a watt is equal to a *volt* multiplied by an *ampere*, it is easy to see that watt-hours must equal *volts* multiplied by *amperes* and *time*; or stated in a formula, we have

$$\text{Watt-hours} = E \times I \times \text{Hours}.$$

In many cases the unit "watt-hour" is too small for practical computations and, for convenience, a larger multiple of the unit is employed, called a "kilowatt-hour." Remember that one kilowatt equals 1000 watts. Therefore, a kilowatt-hour is found by first multiplying volts by amperes by hours, and then dividing the product found by 1000. From this we obtain the following formula:

$$\text{Kilowatt-hours} = \text{Kilowatts} \times \text{Hours}$$

or

$$\text{Kw.-Hours} = \frac{E \times I \times \text{Hours}}{1000}.$$

*One kilowatt-hour is defined as the equivalent of one kilowatt* (1000 *watts*) *of electrical energy expended in one hour.*

The following are examples of the use of the term kilowatt-hour. Suppose that a generator in a power plant is kept in operation to furnish light and power for a factory. If the output of this generator indicates that one kw. of electrical work is maintained for one hour the factory will use 1 kilowatt-hour; or if 2 kw. is maintained for one-half hour ($2 \times \frac{1}{2} = 1$) the factory will likewise use 1 kilowatt-hour; but if 4 kw. is maintained $2\frac{1}{2}$ hours the factory will use 10 kilowatt-hours.

**Illustrating the Proper Use of the Terms: Power, Force, Work and Energy.**—Let us refer to the drawing in Figure 7 where two horses are at work raising a heavy iron beam. This illustrates how force applied through a certain distance causes or tends to cause a body to be set into motion. In this instance, motion is actually produced because the horses are strong enough to perform the task imposed upon them. In this action the *force* might be defined as the physical exertion put forth by the horses in accomplishing the work. The capacity which these horses possess for doing work of this kind is the *energy*. (*Note:* The energy cannot actually be created; it is a natural condition existing within the horses.) The *work* done is the result of the force exerted, or power expended, by the horses in overcoming any opposition or resistance which the load presents. The heavy iron beam is the load. The *power* is the rate at which the work is done, that is, whether it takes the horse fifteen minutes, or one hour, or any given time to

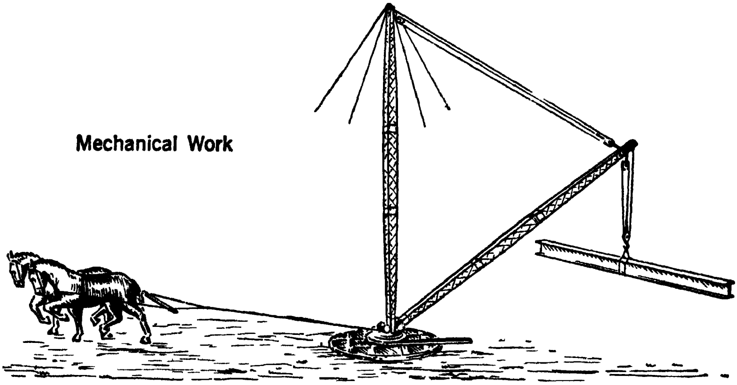


FIG. 7.—Illustrating the application of "mechanical" horse-power.

lift the load. The *total work* includes the power expended and the time.

In summarizing the foregoing facts we can say in a few words that the energy possessed by the horses was converted into mechanical pulling or lifting power. This gives us a good illustration of the laws governing the "conservation of energy." Conservation relates to the transference of energy from one state to another. There is nothing lost, practically speaking, in the transference of energy from one state to another so long as our purpose is fulfilled, that is, so long as the work we desire to be performed is actually completed.

## MECHANICAL AND ELECTRICAL HORSE-POWER DEFINED

**Mechanical H.P.**—In the illustration in Figure 7, we have shown two horses lifting a heavy iron beam by means of a hoisting crane. The power in this case is the rate at which the work of lifting the beam is accomplished. Mechanical work is measured in "foot-pounds" or "pounds multiplied by feet." Thus, if a weight of 3 lbs. is raised to a height of 5 ft. we have an equivalent of 15 foot-pounds of work. Suppose a 7½-lb. weight is lifted only 2 ft.; we would have exactly the same amount of work done as when 3 lbs. is raised 5 ft., or 15 foot-pounds in both cases.

Now, to explain the meaning of mechanical horse-power let us suppose that the iron beam in Figure 7 weighs 33,000 lbs. and is to be raised 1 ft. against the force of gravity, and suppose further that the horses take one minute to do this. Here we have a set of given values. Let us repeat them: 33,000 lbs. is to be raised one foot in one minute. This combination of values is the basis for computing the rate of doing work which is equal to 1 *mechanical horse-power.* If twice this weight, or 66,000 lbs., is raised 1 ft. in twice the time, or two minutes, the "rate of working" would still be the same as in the preceding case, or 1 *mechanical horse-power.*

If the horses were replaced by a stronger team that could lift the same beam the same distance in just half the time, or, let us say, in ½ minute, then it is logical to assume that one team is twice as powerful as the other. Thus, if 33,000 lbs. is lifted one foot in 30 seconds it would give us 2 mechanical horse-power. We see that both teams of horses perform exactly the same total amount of work, but the time required for completing the work, whether 1 hour, $\frac{1}{2}$ hour, or 5 minutes, or any other interval of time, will determine the "time rate of doing the work," or "the power." Mechanical power is usually estimated in foot-pounds per minute, but in some practical work it may be more convenient to use foot-pounds per second. Thus:

1 MECHANICAL H.P. = 33,000 FT.-LBS. PER MINUTE.

or

1 MECHANICAL H.P. = 550 FT.-LBS. PER SECOND.

We obtain the 550 in the lower equation, for expressing so many foot-pounds *per second,* by dividing 33,000 foot-pounds per minute by 60 seconds, that is, 33,000 ÷ 60 = 550.

In commercial practice the power is estimated according to the amount of work done in *horse-power* and the period of time involved in hours.

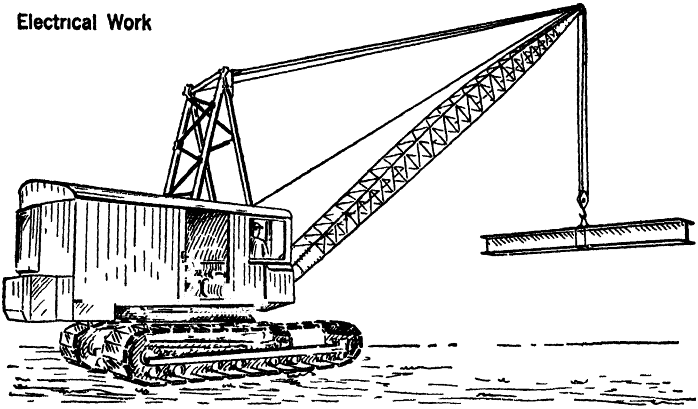


FIG. 8.—A sketch to show the application of "electrical" horse-power.

**Electrical H.P.**—Electrical power is measured in watts, the measurements being based upon the *second of time* and not the minute, which is used chiefly in mechanical work.

Let us suppose the horses in Figure 7 are replaced by an electric motor as the source of power, as in Figure 8. You will recall that power is estimated according to the amount of work done during a certain period of time. Accordingly, in our computations it will be necessary to know the amount of power that a motor is supplying and the length of time it is kept in operation.

In one of the paragraphs in this chapter, under the unit "Joule," it was explained that one joule per second is the unit of electrical power, or the watt. Furthermore, it was explained that the rate in watts at which electrical energy is expended is equal to the voltage of a circuit times the number of amperes of current flowing. Putting these statements together should give you an understanding of the significance of the watts formula; where

$$\text{Watts} = E \times I.$$

Also, from these statements it is a simple matter of deduction to determine that electrical horse-power is equal to watts divided by time, or

$$\text{Electrical H.P.} = \frac{\text{Watts}}{\text{Time}}.$$

Where large amounts of power are handled it is often inconvenient to use a unit as small as the watt, as previously mentioned, and so in the practical work of rating electrical machinery the larger unit "electrical horse-power" is employed. It will be recalled that one electrical horse-power equals 746 watts.

Now, in order to find the rating of an electrical machine, in the unit of horse-power, we have simply to know its capacity in volts and amperes; to find the horse-power multiply the volts by amperes and divide by 746. This is the same thing as saying that the number of watts are divided by 746. Hence, we have:

$$\text{Electrical H.P.} = \frac{\text{Volts} \times \text{Amperes}}{746} = \frac{\text{Watts}}{746}.$$

The following worked-out example is given to aid you in solving problems of this kind. The results can be expressed either in the unit watt, kilowatt, or electrical H.P.

PROBLEM: Suppose the current drawn by the motor in Figure 8 is 20 amperes and the line voltage is 220 volts. Find the number of watts of energy consumed.

*Solution:*

(1) Write formula WATTS $= E \times I$

(2) Substitute known values: WATTS $= 220 \times 20$

(3) Solving, we get WATTS $=$ 4400 watts. *Ans.*

If we wish to express the above answer in horse-power maintained by the motor, simply divide 4400 by 746, or

$$\text{ELECTRICAL HORSE-POWER} = \frac{\text{WATTS}}{746} = \frac{4400}{746} = 5.8 \text{ H.P.}$$

Or, the answer expressed in kilowatts is $4400 \div 1000 = 4.4$ kw.

**Basis of Comparison between Mechanical and Electrical H.P.**—The basis for comparing an equivalent amount of mechanical energy measured in "foot-pounds" and electrical energy in "watts" was worked out mathematically many years ago by Dr. Joule. He made a direct comparison between both kinds of energy in performing exactly the same work, which consisted of heating a given quantity of water until its temperature was raised to a certain value. In the case of mechanical energy the heat was obtained from the friction set up when paddle-wheels were rotated through the water. The amount of power required was figured from the number of foot-pounds of work per second obtained from a certain arrangement of pulleys and weights used in the experiment. In the case of the electrical circuit the power was computed from the amount of current consumed at a certain voltage and the time required in generating the specified amount of heat. Dr. Joule estimated that 1 foot-pound per second is equal to 1.356 watts.

We have already given an equation which states that 550 foot-pounds per second is equivalent to 1 mechanical horse-power. The electrical equivalent of this, or 1 electrical horse-power, would be:

$$1 \text{ ELECTRICAL H.P.} = \frac{550}{0.7375}, \text{ or } 746 \text{ watts.}$$

**The Meter** is the unit of measurement for wavelength. Wavelength can also be expressed in terms of *frequency.* These terms are used in connection with electromagnetic wave motion in space—by this is meant radio waves in space. Refer to Figure 9, which shows a regularly recurring wave motion which might be set up on the surface of water for instance by striking it with equal intensity at regular intervals with a wooden block.

The term wavelength can best be explained with the aid of a drawing of this kind. After an understanding of the meaning of wavelength is once attained, it is easy to apply it to any form of motion that occurs and recurs at regular intervals.

One wavelength is the distance from crest to crest of the wave in Figure 9, or it may be the distance from trough to trough, which naturally would be the same. Moreover, we could consider any point on one wave impulse and compare it to a similar point on an adjoining wave impulse and say that the distance between these two selected points is one wavelength. Let us try to visualize a wave motion occurring in space, set up by unseen forces. Suppose that an electromagnetic wave is projected from an active transmitting antenna, and that this energy consists of a succession of rapidly recurring impulses in space, due to the disturbance set up in the space medium. The length of each individual wave or complete impulse of the electromagnetic wave motion is considered from a similar viewpoint as each water wave.

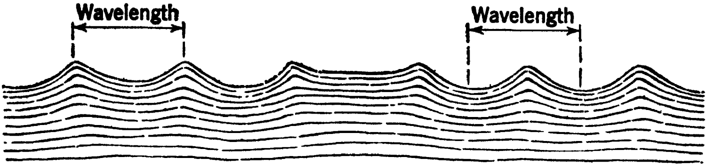


FIG. 9.—Wavelength illustrated by wave motion set up on the surface of a body of water.

The metric unit of measurement is used to compute such distance. Thus the wavelength of an electromagnetic wave sent out by a radio transmitter may be 300 meters, or it may be 1500 meters or 14.5 meters or any desired length which is governed by the electrical adjustments of the transmitter. One meter equals 39.37 inches. The student must not confuse the distance which a radio signal wave will actually travel to be intercepted and heard at the receiving station (which may be several thousand miles in some cases) with the wavelength of each individual impulse in the complete wave motion.

## PROBLEMS ON CHAPTER I

**1.** What is the difference between work and power? What is force and energy? Use an analogy, if you wish, in order to explain the meanings.

**2.** Suppose the capacity of a generator when carrying a load is 3500 watts. Express this value in kilowatts and horse-power.

> *Note:* In answering the following four problems which relate to direct-current circuits use the form suggested in worked-out examples in this chapter where the formula is written first, the known values substituted next, and so on.

**3.** If a current of 2 amperes flows through the lamp in Figure 6, and the line voltage at the wall outlet is 110 volts, what power is being expended?

**4.** Suppose an electrical heater, rated at 350 watts, is placed in operation and by measuring the current strength with an ammeter, we find it to be 3 amperes. Find the line-voltage.

**5.** If the load on a generator supplying an electrical circuit is such that a current of 200 amperes flows at a pressure of 120 volts what is the capacity of this machine in watts? Also, in kilowatts?

**6.** In this problem you are given the following data: The e.m.f. is 120 volts, the current drawn is 20 amperes and the generator is maintained in operation 12 hours. Find kilowatt-hours of energy expended.

**7.** (*a*) Write the formula you would use if the power and current of a circuit were known and you were asked to find voltage.
(*b*) Write the formula you would use to find current strength if the voltage and wattage of a circuit were known.

**8.** Give the definitions of the following units, expressing them in your own words. Do not use the exact wording given in the text.

(*a*) volt
(*b*) ampere
(*c*) ohm
(*d*) coulomb
(*e*) watt
(*f*) henry
(*g*) farad
(*h*) kilowatt-hour
(*i*) ampere-hour

**9.** (*a*) What is a megohm? (*b*) microhm? (*c*) kilowatt? (*d*) micro-microfarad? (*e*) microfarad?

**10.** (*a*) Can energy be created?
(*b*) Name two practical sources for obtaining electrical pressure.
(*c*) What must we first have in an electrical circuit before current will flow?
(*d*) What unit of time is electrical measurement based on?
(*e*) How would you write 35 mmfd. in the unit mfd.?

# CHAPTER II

## ELECTRON THEORY—STATIC ELECTRICITY

IN THIS CHAPTER WE DEAL WITH THE ELECTRON THEORY OF SUBSTANCE AND MATTER, WHICH ACCOUNTS FOR THE WONDERFUL ELECTRICAL ACTIONS DISPLAYED BY NATURE ON AND ABOUT OUR EARTH

**Introduction.**—It might be said that anyone who decides to study the science of radio and electricity introduces himself into a world of unseen forces, or into what is virtually a realm of tremendous activity and agitation. If all of the human beings on this earth were permitted to peer into the mysteries of our world through a huge magnifying glass, one equipped with a lens having a magnification thousands of times greater than the most powerful in use today, it is thought that we would be privileged to gaze upon billions and billions of tiny universes consisting of diminutive specks or particles. Each and every one of these particles is supposed to have all of the three qualities that would entitle it to be classified as a tiny bit of matter. These qualities are *size, weight,* and *mass,* and, moreover, each particle would be found to possess a very definite amount of energy. Energy cannot be created by man in any way whatsoever; the energy existing in the particles is a natural condition and is a part of all things creative, a condition over which we have no control and about which we know little.

The great privilege of seeing these bits of matter is not yet within the reach of man, even with all the available scientific apparatus, because of the natural limitations of our eyesight. We wonder, then, how small these very tiny things really are.

The principal constituents of these minute universes have been given the names *molecule, atom* and *electron.* For years scientists have labored to tear down the clouds of uncertainty surrounding these minute bodies in order that they may learn more about their physical make-up and the particular quality which has been given the name *energy*. How well these tireless laboratory workers have succeeded in putting natural forces to work could never be fully realized unless through some extraordinary calamity everything electrical were suddenly taken from us.

If you could visit the scientific laboratories of Dr. Langmuir, Dr. Coolidge, Dr. Millikan, Dr. Alexanderson, and other scientists of equal prominence, and witness the many marvelous experiments in progress and see the wonderful things that are accomplished when the power locked up in a molecule is utilized, you would appreciate why this chapter on the elements of radio and electricity has been introduced in this way. If you could watch these scientific investigators at work you would undoubtedly forget, at least for the time, about all the ordinary things in your daily existence.

The predominating scientific thought of today teaches us that *everything we see or feel is electrical in nature*, and this despite the fact that we may not be aware of it. The development of such an idea has been a slow one, because it required many proofs to substantiate it, and these proofs could be obtained only through logical reasoning and simple deductions following years of experimentation and research. The idea is now moulded into a well-founded theory, called the "Electron Theory." This theory is used by practically all scientific men to account for different electrical phenomena, and therefore its importance to us cannot be overestimated.

The "Electron Theory," concisely explained in subsequent paragraphs, is based upon the combined action of the "negative electron," the very smallest speck of matter, which is *negative electricity*, and a complementary particle of *positive electricity*. One authority calls the latter a "positive electron," but it is more commonly spoken of as a "proton." These electrical charges not only form the basis of all matter itself, but are the cause of all electrical actions. Thus, better to understand electrical forces and their practical application, it is necessary to have some general information concerning the construction of matter.

**Matter.**—All normal human beings are gifted with five faculties or sensations; these are *sight*, *taste*, *hearing*, *touch*, and *smell*.

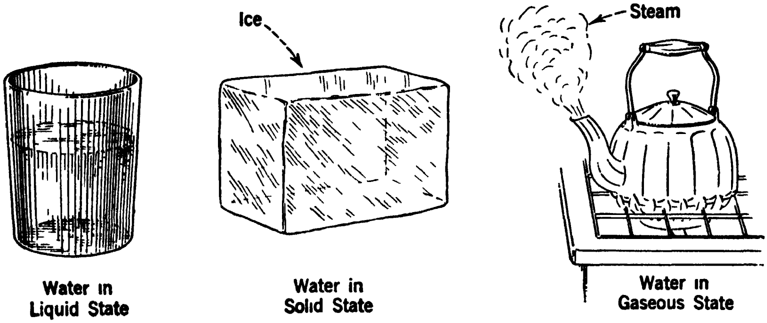
Scientists tell us that anything which occupies space and acts on our senses is *matter.* If we accept this statement we should have no difficulty in understanding that objects, such as chairs, tables, houses, radio sets, the wires used to connect up radio parts, aircraft, the very paper and ink used to print this book, and even the air you breathe, are all examples of matter. *Again, anything which occupies space and has weight is said to be matter.*

Matter taken as a whole exists in three different forms, namely:

## SOLIDS, LIQUIDS AND GASES

A *solid* is a body which offers an opposition to any change in its shape when under normal temperature and pressure. An object such as a piece of iron will keep its shape and identity just so long as it is protected from the elements, or from abnormal temperatures or pressures.

However, we know that if iron is placed in a blacksmith's forge and heated it can be worked into any desired shape by constant pounding with a hammer. Striking the hot iron with a hammer exerts a certain pressure, and the hot fire increases the temperature; it is clear that these two provisions are necessary before the iron can be properly worked. Now, suppose this iron remains in the fire bed and the heat is considerably raised by operating the forge blower; it is evident that a time will come when the solid piece of iron will become molten and then, being



**Water in Liquid State**

**Water in Solid State**

**Water in Gaseous State**

Fig 10.—Water may be converted or changed from one state to another as shown in these sketches.

converted to a *liquid,* it will either form a pool, or run off, or flow as would any heavy fluid. If the liquid iron was poured into a receptacle, or mould, and allowed to cool, it would assume the shape of the mould.

Water is a very good example of matter which can be easily changed into any one of three forms. Water in its natural state is a colorless liquid; when frozen it turns into a solid cake of ice; and when heated to the boiling-point steam will issue forth from its surface and rapidly expand into the surrounding space as a *gas.* See Figure 10. In general, all forms of matter have four important properties. They are:

## POROSITY, COMPRESSIBILITY, ELASTICITY AND DIVISIBILITY

(*a*) *Porosity* may be defined as the existence of minute openings or pores in any kind of matter, the openings or pores being entirely void of any of the material or substance of which the matter is composed. Each pore, regardless of its size, is really empty space. These openings vary in size for different materials, as may be seen by inspecting a section of soft wood and comparing it with a piece of marble or iron. The common blotter which absorbs ink is a good example of porosity. Also, water is capable of taking into its pores a definite amount of dissolved sugar without noticeably increasing the bulk of the water.

(*b*) *Compressibility* may be considered to be a general property of all matter which would permit the small particles composing the matter to be more closely packed together. This packing would tend to lessen the amount of the void spaces within the mass. Pressure applied to any substance acts to compress it. A hot ingot of iron, after passing through heavy steel rollers in a steel mill, will emerge in compressed form. In the case of water and oil we have forms of matter which almost resist compression; however, such liquids may be compressed to a very limited degree by the application of great pressure. In all events the amount of compression depends upon the pressure exerted and the kind of matter under compression.

(*c*) *Elasticity* of matter may relate either to elasticity of physical form or elasticity of volume. This term is used to designate the property possessed by solid bodies that permits them to be stretched to certain limits without breaking and, later, to return to their original shapes after the stretching force or pressure is removed. When force is applied to a material in a way that will cause it to become twisted, bent, or stretched, the molecules which form the material are distorted and displaced under an unnatural strain. If the force is discontinued the molecules will try to adjust themselves and shift back into their usual places as quickly as possible.

This property, known as "elasticity," can be demonstrated by pulling a rubber band and then letting it go. It is this property of elasticity that permits heavy weights to be supported with safety. It would require a far greater force to pull a copper wire in two than a piece of silk. Thus, we would say that the wire has greater *tenacity* than the silk, or we might say the molecules forming the wire will not "let go" as readily as would the molecules of silk. All solids and liquids and gases have elasticity to a greater or lesser extent.

If force is applied in constantly bending a material, heat will be generated. This is due to the rubbing together of the molecules as they are forced out of their relative positions; we say that the heat is due to *molecular friction.*

(*d*) *Divisibility* of matter relates to the division or breaking up of matter into its smallest conceivable parts without in any way altering the form of matter itself. Just how small such particles of matter may actually become, and still retain their identity, can be demonstrated by allowing a few drops of colored ink to fall into a glass of water. At first the ink will be seen to form irregular streaks which work downward through the liquid. If the glass is left undisturbed for some time it will be noticed that all of the liquid will become colored. Can you imagine how tiny these divided ink particles (from only a few drops) must have been to permit them to enter the countless pores in the comparatively large volume of water, and cause the water to be uniformly colored throughout?

Hence, we learn that matter is not absolutely a solid homogeneous structure, but that matter is made up of countless billions of extremely little particles with non-material spaces, called "voids," separating the particles.

The exceedingly minute particles which we have been speaking about are given the name *molecules*, and they are never absolutely motionless under average conditions.

**Molecules.**—A molecule is defined as the smallest division of any kind of matter retaining all the chemical and physical properties of the matter itself. Therefore, a molecule, although very small, can be identified as belonging to a particular kind of matter.

As a body is lowered in temperature, that is, as it gets colder, the movements of the molecules become less violent. On the contrary, when a body is raised in temperature, that is, as it gets hotter, the molecular movement becomes increasingly more active. It is only at the very lowest known temperature (absolute zero) that the molecules of all matter are dormant, meaning that all action ceases. Absolute zero is about 459 degrees below zero and is the point at which no heat can be given up or taken from a body. Speaking in broad terms we can say that heat encourages molecular vibration, or motion, whereas cold tends to counteract it.

**Atoms.**—The molecule itself is composed of an aggregation of atoms, the atoms being the smallest parts into which matter can be divided by chemical means. The tendency of atoms of a similar kind (or species) is to assemble together and form molecular groups which in turn become units of matter. Once the groups are assembled they resist all ordinary methods employed to disrupt or tear them apart. The application of a force and the use of heat are two means for effectively overcoming the strong molecular attraction inherent in all matter. An atom consists essentially of positive and negative electricity with the atoms of the various materials differing in their general formation.

There are more than ninety different species or kinds of atoms, some of which are familiar to all of us; for example, we have the copper atom, the iron atom, the gold atom, the hydrogen atom, and so on. The individual atoms in any one species are practically identical, but the different species have totally different properties.

**Elements.**—Every molecule which forms a given substance must consist of the same number and same species of atoms, and to express this fact we give the substance the name *element*. Taking any of the elements singly, each one consists of only one kind of atom. Hence, we understand now why copper, sulphur, iridium, oxygen, carbon, lead, gold, and all the rest of the ninety or more elements each exhibit their individual properties by which we know them. When different kinds of atoms combine the substance formed is called a *compound.*

You can better understand these terms by analyzing how water is formed. Water, as we know it, is simply a colorless liquid. A molecule of water is the smallest divisible part of water that can possibly be obtained with the molecule retaining the identity of water. However, the molecule is composed of two elements, neither one of which resembles water.

These elements are hydrogen and oxygen, two gases which always combine in certain amounts when brought together. To cite an example: It takes two atoms of hydrogen to enter into combination with one atom of oxygen to form one molecule of water and, using the symbols, we have the chemical expression for water, $H_2O$. A water molecule is a very simple arrangement in the atomic world when compared with a molecule of certain compounded substances. We, have, for example, a very complex aggregation of different species of atoms in a molecule of sugar. To form one molecule of sugar requires twelve atoms of carbon, twenty-two atoms of nydrogen, and eleven atoms of oxygen, combined into a single group. There are countless numbers of possible molecular combinations which permit the formation of the many different kinds of things found in and about this world of ours.

**Cohesion.**—There is a tremendous mutual force of attraction between atoms of certain kinds that causes them to form groups, and because the atoms possess this property the molecules which they form also have it. Thus, we see why there is a strong tendency for things to hold or cling together, or remain intact—this property of matter is called *cohesion.*

You might be surprised to learn that it is not a simple matter to pull a sheet of paper apart. Why not try to do this right now and convince yourself? Take a sheet of writing paper, roll it and then grasp it at either end and pull with all your effort. Were you successful in pulling the paper into two parts? Although you can tear this paper easily, you may not be able to force the molecules to give up their clinging hold on one another.

The term *adhesion* is often confused with *cohesion.* Adhesion is used to express the mutual forces that hold molecules of dissimilar kind together. Butter will stick to bread because of *adhesion,* but the butter or bread considered alone hold together because of *cohesion.*

**Electricity is Divided Generally into Two Classes.**—In the broad sense electricity is divided into two classifications, namely: *static electricity* and *dynamic or current electricity.* A brief outline of important early experiments which deal mainly with static electricity will now be presented. You will see that many electrical principles can be explained and proved by the simplest facts of nature and by laboratory experiments.

**Important Events Leading up to the Establishment of the Electron Theory.**—Going back to the year 600 B.C. we find that in the Grecian city of Miletus there was a Greek philosopher, named Thales, who pondered over the causes of lightning and tried to ascertain why it had such destructive effects. During one of these periods of study he discovered, quite by accident, that if an amber rod was rubbed with a piece of silk the rod at once possessed the power to attract small bits of parchment. Later, during the period around 400 B.C., Democritus devoted considerable time to the study of materials and effects which could be produced by them, when treated in various ways. His interest was aroused when he observed that in some instances an attraction was set up between certain substances when rubbed together, whereas between other substances the effect of repulsion was set up.

These experiments are thought to be among the very first recorded concerning the discovery of a source of electricity, and since the effects were brought about by friction this kind of electricity became known as "electricity at rest." But we now call effects of this kind "static electricity." The ancient Greeks attempted to account for the mysterious results obtained by rubbing together materials of different kinds. One of the reasons they advanced in explanation of such effects was that during the rubbing process small grains of one material were being imparted to the other material.

In 1600 Dr. Gilbert of England performed experiments similar to those of the Greeks. But where they used amber he employed a glass rod, and observed that the materials could be put into a condition that would give them the power of attraction or repulsion as the case may be. It was Dr. Gilbert who applied the Greek work for amber, which is "elektron," to express these peculiar effects, and he stated that when the glass rod was rubbed it became "electrified." The electrification of bodies when subjected to such treatment was shown to be merely a temporary condition, and although the exact nature of the electrical charge was not known, the results attained indicated that *the static charge rested only on the outer surface of the electrified material.*

In 1733 Dr. Dufay, when engaged in frictional electrical experiments, noticed that sealing-wax, when rubbed with cat's fur, became electrified and possessed qualities unlike those of a piece of glass which had been electrified by rubbing with cat's fur. He saw that the sealing-wax would repel substances for which the glass, on the contrary, would exhibit a decided attraction.

Moreover, he sought to identify these properties of opposite kind. Accordingly, he gave the name "resinous electricity" to the charge possessed by sealing-wax when rubbed with cat's fur and the name "vitreous electricity" to the charge taken on by glass when subjected to frictional contact with the cat's fur. Thus, we must learn at the start that the terms *positive* and *negative* in all electrical science are merely relative and arbitrary as originated by Franklin. Indeed, he could have called resinous and vitreous electricity by totally different names so long as the names he did apply served to illustrate the important fact: "*Whenever electricity is evident there always exists simultaneously two unlike electrical charges of equal quantity.*" You cannot have one kind of charge present without the other. The words "positive" and "negative" seemed to fit the requirements, and they have been used as standard terms ever since.

**Meaning of " Positive " and " Negative."**—We are indebted to Benjamin Franklin for originating what are undoubtedly the two most commonly used terms in electricity; namely, *positive* and *negative.* About the year 1747, after considerable experimental work, he observed that whenever electricity of one kind was present there also was present an opposite kind. In other words, we could not have one condition of electricity prevailing without also the opposite condition. From this fundamental idea we are able to account for the effects of attraction and repulsion. Franklin suggested that the state of charge be given the following arbitrary terms, thus: "A substance is said to be *positively electrified* if it is repelled when coming into contact with a glass rod after the latter has been electrified by rubbing with silk. On the other hand, a substance is said to be *negatively electrified,* or charged to a negative sense, if sealing wax repels it after the wax has been electrified with cat's fur."

It is interesting to note that in the early days learned men believed electricity was due to the flow of an invisible liquid. Indeed, even to present time we use the word "flow" to express the movement of an electrical charge from one place to another. In our everyday work we often hear someone make the following remark: "A flow of current in a certain conductor produced such and such a result, etc." Thus, the term "flow " has been retained despite the fact that the fluid theory has long since been discarded.

In 1833 Faraday also contributed theories concerning the electrical effects resulting from friction between substances. He conceived the idea that when materials were rubbed together they were placed under an electrical influence, or stress, and that some unknown intervening medium was capable of carrying this stress along the material. This is precisely what happens when a glass rod is rubbed with a silk cloth. This conception was really important because it was the forerunner of the idea that the surrounding "space medium" was a carrier of an electrical charge.

Furthermore, it is important to mention that Faraday discovered that a distinct relationship existed between substance and current. This relationship was observed by him when performing an experiment employing a jar containing a solution in which was immersed a copper rod and a silver rod. He noticed that a certain amount of current was required to maintain a chemical reaction which would remove a certain quantity of silver from the silver rod and deposit it on the copper.

After Stoney's suggestion in 1891 that the "electron be known as the natural unit of electricity" the electron theory became permanently established. But notwithstanding the many years of diligent research, as just outlined in this chapter, the question, "What is electricity?" remains unanswered to this day. No one is certain as to the actual nature of electricity.

**The Electron Theory Accounts for Electrical Forces and Their Effects.**—At the present time the electron theory prevails almost universally. It is based on the very nature and composition of all matter, solids, liquids, and gases. All forms of research are vitally important because as modern science delves closer and closer into the fundamental basis of our universe it daily contributes new knowledge which makes possible the rapid development and improvement in radio and electrical design and equipment.

Getting down to the last analysis of matter, or its real composition, we are told that it is all made up of infinitesimally small matter particles which are essentially electrical charges. These unit charges of matter have been given the names *electrons* and *protons*. In brief, all electrons possess a definite amount of negative electrical energy; also, they constantly whirl about their positive nucleus at tremendously high velocities, besides which they occupy a certain place in the complicated system in the atoms of matter. In this text we shall deal chiefly with the "electron" and simply refer to the "proton" as the positive charge or nucleus. The exact arrangement of this atomic system depends upon and differs according to various kinds of matter. Refer to Figure 11, where we have attempted to show the arrangement for three different atoms, each with an inner group of electrons circling about a positive center of attraction, and "free" electrons

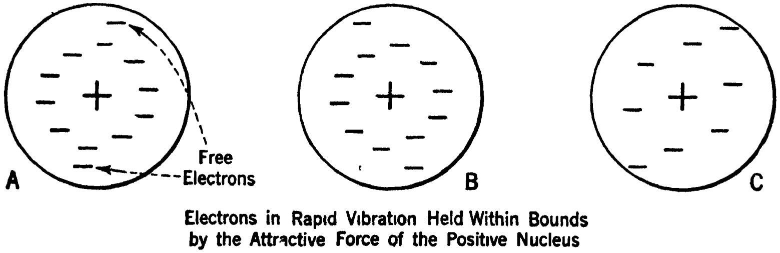

A
Free Electrons
B
C
Electrons in Rapid Vibration Held Within Bounds by the Attractive Force of the Positive Nucleus

FIG. 11.—The three sketches of atoms are intended to show in picture form some of the different arrangements possible between electrons and their positive nucleuses.

racing about at high velocity to form a so-called outer group. Note that because of their position the free electrons could be more easily detached from an atom than any of the electrons forming the inner group.

This hypothesis, wherein atoms of matter are thought to be made up of electrons, or particles of electricity, teaches us that electricity and matter are fundamentally the same. Before you are through with this subject you will learn not only that all matter is made up of a very complex and wonderful structure of atoms, but that the basis of all things is the small unseen electrical particle "the electron."

## FRICTIONAL OR STATIC ELECTRICITY

Let us now return to our subject and discuss in detail the results of performing a simple experiment where two dissimilar substances are rubbed together, and electrical forces are developed. There is no movement to electrical forces of this kind in the ordinary sense that one usually thinks of movement; the forces are "stationary," or better expressed as "*electricity at rest.*" Forces of this kind are known as "*static electricity,*" and the subject itself is referred to in general as **Electrostatics.**

It will be shown that static electricity produces effects which are independent and different from those resulting from "*electricity in motion.*" The latter kind of electricity is classified in general as dynamic electricity, or as **Current Electricity.** This is the electricity that flows through copper wires and other conducting mediums and is referred to in general as **Electrodynamics.**

**How to Produce Electricity by Simple Methods.**—It is an easy matter for us to observe the effects of static electricity produced on materials by rubbing them together. To do this follow the instructions as suggested in Figures 12 and 13. Take an ordinary rubber comb and with the back held against a piece of wool rub the comb briskly back and forth across the wool. The comb is now electrified. If you now move it close to small bits of paper, which have been prepared for the experiment, a very strange influence will be seen to exist in the region about the comb. You will notice as the comb is moved slowly toward the little paper bits that they will be strongly attracted to it; the bits will actually jump toward the comb and adhere to it for a few moments. Next, as you watch this action, you will observe another peculiar effect, for after a short interval the bits of paper will seem to be thrown forcibly away from the comb. That is to say, the paper bits do not merely drop off but seem to be actually repelled. In the first part of the experiment the property of attraction between the materials was observed, and, lastly, the property of repulsion was clearly exhibited. This is only one of many effects which may be brought about by static electricity due to friction.

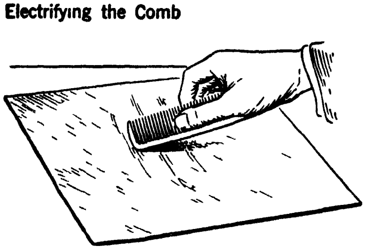


Fig. 12.—A simple means for producing static electricity on certain materials by rubbing them together.

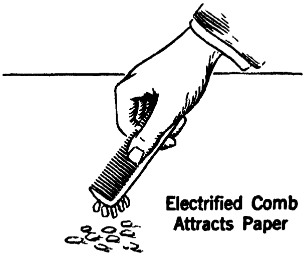


Fig 13.—The proof of static electricity.

Inasmuch as the comb at different times evidences qualities which are opposite electrically, that is, alternately indicating attraction and repulsion, then it sets us to thinking that unseen forces must have been constantly at work while this entire experiment was under way. It is quite apparent that two distinct kinds of electric (static) charges were present in order to produce these results.

Let us experiment further and perform a simple test similar to one made by Franklin in 1747. His purpose at the time was to evolve standard terms to be used in explaining actions relating to electrical (static) forces from known conditions. Our purpose, it is quite obvious, is merely to learn about this marvelous science, so let us set up the experiment as illustrated in Figures 14 and 15. A glass rod and an ebony rod are each suspended by a silk thread at some distance from each other as shown in the drawings. A second glass rod will be used to produce the desired effects by touching it first to one of the suspended rods and then the other.

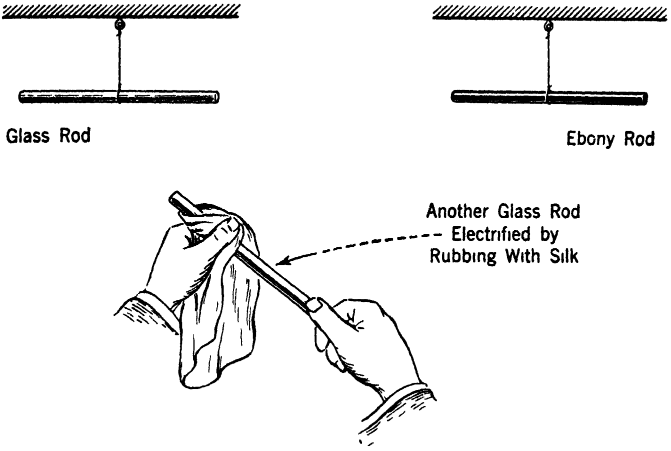

Glass Rod
Ebony Rod
Another Glass Rod Electrified by Rubbing With Silk

FIG 14.—An experiment to demonstrate the attractive and repulsive influence of electrified or statically charged bodies

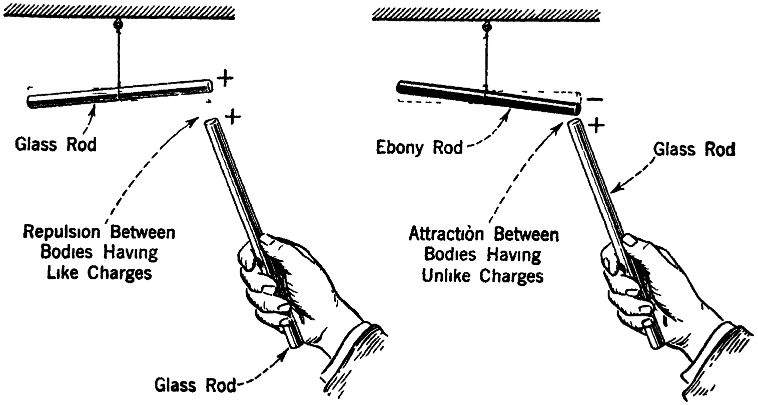

+
+
Glass Rod
Repulsion Between Bodies Having Like Charges
Glass Rod
−
+
Ebony Rod
Glass Rod
Attraction Between Bodies Having Unlike Charges

FIG. 15.—These experiments illustrate how charged bodies influence each other when in close proximity.

Now, with a brisk movement, rub the ebony with a piece of fur and then rub each glass rod in succession with a piece of silk.

The three rods are now said to be *statically charged* or *electrified.* Take the unsupported glass rod and hold it near the ebony rod. The ebony rod will at once swing toward the glass rod, thus denoting the presence of an *attractive* influence. This time place the glass rod, held in the hand, close to the supported glass rod. The latter will be seen to swing away instantly, thus denoting the presence of a *repulsive* influence. The sketches in Figures 16 and 17 illustrate the unseen forces that are thought to cause attraction and repulsion effects in static electricity.

**Electric or Static Field.**—The experiment in Figure 15 shows how one electrically charged body exercises an influence on another charged body when they are placed in close proximity with each other. The drawings in Figures 16 and 17 are a simple means for showing how "lines of force," which are called "static lines of force," reach out a considerable distance and occupy the space surrounding an electrified body. These lines are, of course, invisible, but the static electrical actions are accounted for by their presence.

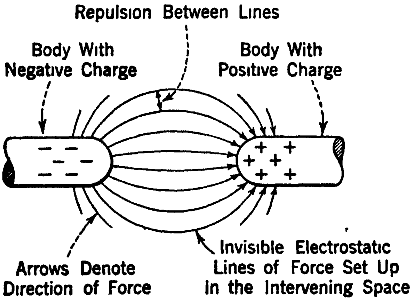

Repulsion Between Lines
Body With Negative Charge
Body With Positive Charge
Arrows Denote Direction of Force
Invisible Electrostatic Lines of Force Set Up in the Intervening Space

Fig. 16.—Two charged bodies of unlike polarity exhibit "attraction" between them when brought near each other.

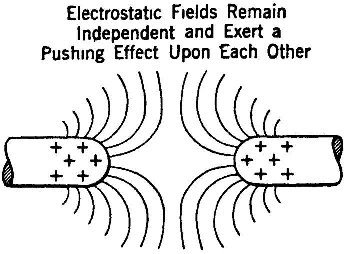

Electrostatic Fields Remain Independent and Exert a Pushing Effect Upon Each Other

Fig. 17.—Repulsion is manifested between bodies charged with electricity of like polarity.

A "force" is always indicated by a line, and the direction of the arrow-head at the end of the line denotes the direction in which the force is applied. Also, understand that the individual lines show repulsion for one another, and it is this peculiarity that causes them to remain apart and assume the formation shown in the drawings. All of the lines taken as a whole are called *a static* *field of force.* The space surrounding a charged body is filled with these static force lines, with the effect of each individual line ending on the outer surface of the material.

From this test we see why a strong *attraction* existed between the ebony and glass rods and a pronounced *repulsion* between the two glass rods. We can now summarize this by stating that the materials were placed in this condition by rubbing and that two kinds of electric (static) charges were made evident; this is indicated by the polarity signs (+) and (−) in Figure 15.

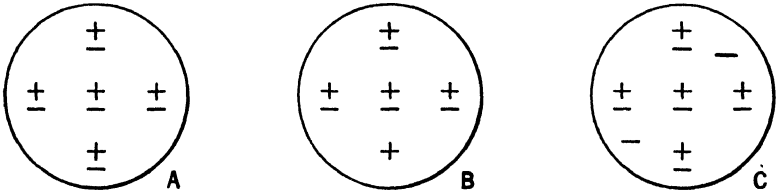
**Static Charges Are Due to a Displacement of Electrons within the Atom.**—With the tests just performed in mind and explanations to follow we will learn why materials exhibit totally different actions when electrified by friction. The fact that glass and fur when rubbed together show contrary electrical behaviors is quite significant. To give a reason why one has the power to "attract," and the other the power to "repel," we must refer back to the construction of matter and how it is based on the atom and the electron. One of the greatest authorities of our day, Robert Andrews Millikan, explains that the differences between all matter, which give us so many varieties of things, are accounted for by the number and variety of the groupings of negative electrons with their positive charges. These opposite electrical charges in combination constitute the atoms of matter. The positive charge within the atom is sometimes called a *proton,* as stated before.

So we learn from the study of the electronic formation of matter that the qualities which permit a particular substance to be recognized are due entirely to a variation of the number of atoms, their size and aggregation in forming the whole mass. We are also told that although the proton of an atom may remain unchanged in position, or quantity, yet it is possible to have perhaps one or more electrons added to or subtracted from those normally revolving within the atom. Any change in the number of electrons in an atom, however, will cause it to become unbalanced electrically. Under such conditions the atoms, and likewise the mass itself, will assume electrical characteristics which are either negative or positive, as explained under the topic immediately following.

It has been proven experimentally by physicists that heat alters the atomic structure of mass. The act of rubbing the glass rod with the silk cloth, as in Figure 14, set up friction between the materials, and this in turn resulted in a certain amount of heat being developed. Hence, under all conditions, we expect friction to generate heat in varying degrees, depending, of course, upon the circumstances surrounding the action. Accordingly, we may expect in the case just cited that the temperature of both the silk and the rod was increased to some extent, although the heat may not have been sufficient for you to detect it. Have you ever noticed how iron, when subjected to intense heat, will at first change its shape somewhat and later become a molten mass and flow like a heavy liquid?

The electrification of the glass rod, according to the electron theory, is due to *a certain displacement of electrons within the atoms by which they are shifted slightly out of the usual positions they occupy.* So long as the electrons remain shifted out of the relative positions in this way, just so long will electric forces (static lines of force) be in evidence in the space about the rod.

**When a Mass is Said to be Electrically in a Neutral, Positive, or Negative State.**—Referring to Figure 18 you will observe three sketches which we use to show pictorially why unit quantities of a mass are capable of displaying electrical properties at different times.



Neutral or Normal State

A Positive Electrical Condition

A Negative Electrical Condition

FIG. 18.—Sketches *B* and *C* illustrate why the unit quantity of mass, sketch *A*, is capable of displaying electrical properties.

(*A*) The left-hand drawing, marked *A*, indicates that the atoms of this unit mass are in a *neutral* or *normal state*, because the charges are exactly equal in amount and opposite in their nature (+) and (−). Each atom is perfectly "balanced" or "neutralized." When atoms are in this condition, which is a normal condition, no external electrical influence is detectable about the mass. When a body ceases to show electrification it is due to the reuniting of the separated charges.

(*B*) However, upon looking at the middle drawing, marked *B*, you will see that there are five positive and four negative charges. Since the amount of positive charge is greater than the negative this unit mass will be *positively charged.* It will be recalled that the glass rod in the experiment of Figure 15 was put into a similar condition of possessing more positive than negative electricity after being rubbed with the silk. This was brought about, it is thought, by a transference of negative charges or electrons from one unit mass to another, or from the glass to the silk. Notice that the unit charge in sketch *B*, Figure 18, did not become a positive one because more positive electricity had been added, but rather because a certain amount of negative electrons had been detached from the neutral mass in sketch *A*. This means that each atom in mass *B* has given up perhaps one or two of its electrons.

Summarizing these statements tells us, in a few words, that if a mass loses any of its electrons the amount of negative charge is reduced and the mass is made positive. When in this condition the mass sets up a force which is continually trying to restore its atoms to normal by attracting the same number of electrons to itself that it lost. This explains why the mass in sketch *B* is said to be *charged positively*, or *charged to a positive potential.*

(*C*) Now turn your attention to the right-hand sketch in Figure 18, marked *C*, where a unit mass is shown with more negative charge than positive. Here the mass is *negatively charged.* Bear in mind that there are the same number of positive charges in all of the three sketches, but that in sketch *B* we took away electrons, whereas in *C* we have put in two additional negative charges. It is clear that there is a predominance (greater amount) of electrons in *C* over that for a normal condition. The net result in this case, where we have an excess of electrons, is to set up about the mass a *force* which is continually trying to discharge or give up these additional electrons to restore its atoms to normal. This explains why the mass in sketch *C* is said to be "charged negatively" or "charged to a negative potential."

## THE ELECTROSCOPE

**A Simple Experiment to Explain "Induction" and "Conduction."**—An electroscope is a sensitive device used to detect minute charges of static electricity. A working model can be easily assembled as shown in Figure 19. It consists of a perfectly clean and dry glass bottle fitted with a cork through the middle of which is inserted a stiff copper wire long enough to protrude from both ends of the cork. The upper end of the wire is bent to form a loop while the lower end is made L shaped in order to hold a sheet of gold leaf folded in half. This arrangement provides a pair of gold leaves which naturally fall together as illustrated. The cork acts to insulate the metal portions from the glass bottle.

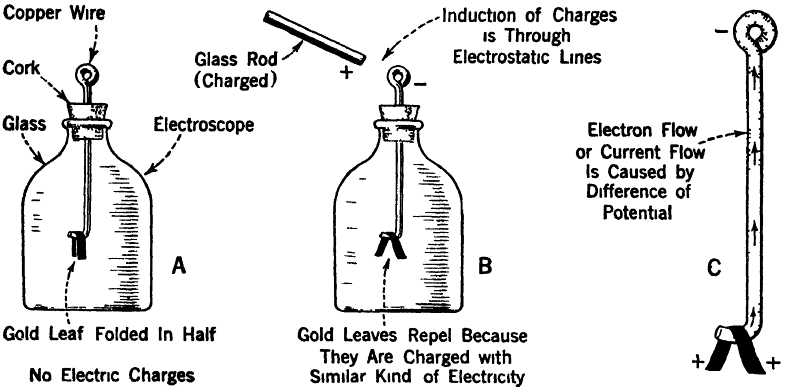

Copper Wire
Cork
Glass
Glass Rod (Charged)
+
Electroscope
Induction of Charges is Through Electrostatic Lines
−
−
Electron Flow or Current Flow Is Caused by Difference of Potential
A
B
C
Gold Leaf Folded In Half
No Electric Charges
Gold Leaves Repel Because They Are Charged with Similar Kind of Electricity
+
+

FIG. 19—The electroscope pictured above may be easily constructed; it furnishes us a simple way to detect minute charges of static electricity

The influence of static electricity upon bodies and the indications of the kind of charges present, that is, whether of positive or negative sign, will be shown by the falling together or spreading apart of the leaves.

To begin our test let us rub a glass rod with silk and then carefully move the rod toward the wire loop without permitting actual physical contact between the respective surfaces. Notice how the leaves spread apart. This is said to happen because an *electric force* or charge of *like kind* is built up on each gold leaf. Since these forces reach out like any electrostatic field and are effective in the region surrounding the leaves, we observe this repulsion between them. The nature of the charges and the entire action is explained below in steps for the sake of clearness:

1. It has been arbitrarily decided, as mentioned heretofore, that a glass rod when electrified by rubbing with silk will be charged with "*positive electricity.*"

2. The glass rod induces a charge of opposite kind on the wire loop, hence the loop becomes charged with "*negative electricity.*"

3. It is seen that the wire and gold leaves taken together actually form a metallic path. In order to make the loop end "negative," as just stated in paragraph (2) above, it was necessary that electrons be *forced* to move from one end of this metallic path to the other. Or, we could express the same thing by saying that electrons were conducted through this metal path by reason of the *potential force* set up at the loop end. Note that the additional electrons which collect at the loop end were originally located at the opposite end, or at the gold leaves. This removal of electrons leaves the latter point deficient in electrons, or with a positive charge. This action is shown in the enlarged view in sketch *C*, Figure 19.

4. Thus, when the loop end is negatively charged or at a negative potential, the opposite end or gold leaf end becomes *positively charged*, or is placed at a *positive potential*, which is the same thing. Comparing both ends there is a difference of potential between them. Consequently, each gold leaf individually possesses a positive charge of equal amount. Therefore, the leaves will diverge or spread apart. This is exactly what would be witnessed during this experiment.

Before putting this experiment aside it is suggested that you again charge the electroscope by induction using the electrified rod and, while the leaves are separated, place your finger on the wire loop. The moment contact is made the leaves will fall together, showing that your body has neutralized the charge. It would be a very simple matter for you to make an electroscope.

**The Difference between the Terms "Induction" and "Conduction."**—Again refer to the electroscope experiment in Figure 19. In so far as the wire and gold leaf are concerned, the positive and negative electricity already existed in the atoms which constitute these metal parts. That is to say, the electricity is always present or inherent in the materials. But this electrification was not separated into positive and negative charges, which we know developed at the opposite ends, until the force represented by the charge on the glass rod induced a charge of opposite kind on the wire loop. The force could be represented in the drawing by the lines in space connecting the respective surfaces of the charged bodies, as seen in Figures 16 and 17. Thus, we may have **induction** of charges even without the surface of bodies actually touching each other.

In the case of the metallic path in the electroscope, Figure 19, it happens that the difference of potential set up between the two ends forces electrons to move from atom to atom through the metal in a direction from the gold leaves toward the loop end. This entire action is the result of the original attractive force exerted by the positively charged glass rod upon the loop of wire.

One important point just mentioned that should be borne in mind is that in the case where the glass rod is electrified there is no movement of electrons throughout the material, but rather a displacement or slight shifting of electrons within the atoms takes place. On the other hand, in the case of the metal parts, electrons do move or are conducted along from atom to atom of the copper and gold, passing from one end of the metal path to the other.

The movement or drift of electrons through the metal parts is actually a flow of current, or "current electricity." Electrons passing through the metal parts illustrates **conduction.**

Accordingly, we may hereafter call the entire path (to include any and all mediums, air, gas, solids, etc.) through which a transference of electricity takes place, or through which electronic current will flow under a given electromotive force, a *conductive circuit.*

The electroscope experiment enables us (1st) to explain the use of the terms "positive," "negative," and "potential," (2d) to observe by means of the gold leaves that *repulsion* is always set up between bodies charged with electricity of *like kind,* and (3d) to demonstrate that positive and negative electricity always appear simultaneously.

Although static electricity and the electrons which account for it are invisible to us, nevertheless the effects they produce can be indirectly observed under certain conditions. We have explained in the next chapter on "magnetism" how a force which acts between magnetized substances also exhibits identical properties of "attraction" and "repulsion," but in the case of magnetism the force is not derived in the same manner as in static electricity.

**A Simple Explanation of the Term Potential.**—Electrons may be likened to potential charges. The term "potential" as applied to forces means that energy is stored up in some manner, not necessarily in an object, or mass, but because of the position the object occupies.

To explain this idea let us cite the following comparison: A stone resting on the ground is not capable of performing work as compared to the same stone placed near the edge of a high cliff. The stone, when resting on the cliff, becomes a *potential force* because, if the stone is pushed, it will fall and a certain amount of work will be done. The work in this case consists of the weight of the mass falling a certain distance through space. Hence, potential deals with a condition in space. The same conditions are true in the case of static electricity and charged bodies. Hence, to make the comparison, we would say that potential does not mean the charge itself, nor the mass or body, but rather a condition that exists at a certain point in space. Refer to the drawings in Figures 16 and 17 showing the static forces set up in the space about the charged bodies as indicated by the arrangement of the lines. "Potential" is a term used in connection with forces, and in our work the term is applied to both static electricity and current electricity.

As an example, the term "potential" is used in regard to an ordinary dry cell or storage battery. The two terminals are connected to electrodes, one of which is said to be at a "positive potential" and the other at a "negative potential." This difference of potential is what provides the electrical pressure and makes the cell or battery capable of performing work. The term potential is also used in business; a potential buyer or potential customer is considered to be a person who has not yet bought any merchandise, but who has the power or is capable of making a purchase if he so desires.

**How to Use the Term Potential. Illustrated by Three Typical Cases.** *Case* 1. In Figure 20 two bodies, *A* and *B*, are shown, one having a positive potential and the other a negative potential of equal amount. When discussing the electrical properties or forces set up by two such bodies we say that between them "there is a difference of potential," and because of this condition an electrostatic field is established.

*Case* 2. Also, we have cases of two charged bodies where each one has a positive potential, but one is at a relatively higher positive potential than the other. See Figure 21. This indicates that bodies *A* and *B* both have a shortage of electrons, but, relatively speaking, body *B* has fewer electrons than body *A*.

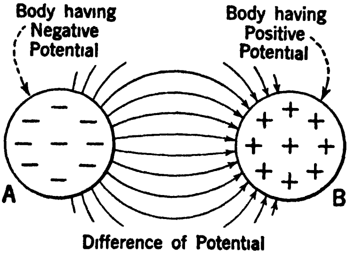

Body having Negative Potential
Body having Positive Potential
A
B
Difference of Potential

FIG. 20.—This drawing shows that when two bodies—one having a positive potential and the other a negative potential—are placed relatively close to each other an electrostatic field is established between them.

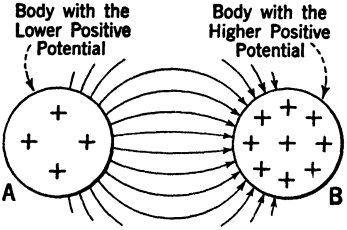

Body with the Lower Positive Potential
Body with the Higher Positive Potential
A
B

FIG. 21.—Two bodies, each having a positive potential but of unequal amounts, also set up electrostatic lines of force.

Thus, body *B* will set up a *force* which places it at a higher potential than *A*. Now on account of this difference of potential, electrons would move from the lower potential point *A* to the higher potential point *B*, providing they were furnished a path or medium through which they could pass. The electrons would move in this direction in their effort to reduce the higher force and bring it down to the level of the lower force. It can be said that *B* is in a more unbalanced state than *A* because more electrons would be required to place *B* in a normal or neutral condition than would be required for *A*. The medium we refer to could be a copper wire, or any other conducting material, or perhaps a gas, or the atmosphere in certain conditions, and so forth.

*Case* 3. Also, there are cases of two charged bodies where each has a negative potential, but of unequal amount, as shown by bodies *A* and *B* in Figure 22. If electrons were given a path between these bodies they would move from *B* to *A* since *B* has a relatively greater amount of excess electrons than *A*. It is said that *B* is charged to a higher negative potential than *A*. Electrons would move toward *A* as suggested in order to equalize the amounts of negative in each body, and, moreover, they would continue passing from one body to the other until no difference of potential existed between the bodies.

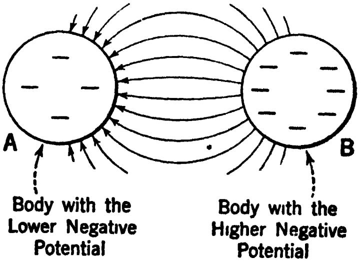

A
B
Body with the Lower Negative Potential
Body with the Higher Negative Potential

FIG. 22.—Two bodies charged with unequal amounts of negative potential likewise set up electrostatic lines of force.

## FUNDAMENTAL ELECTROSTATIC LAWS

We noticed in our experiment with the bits of paper and rubber comb that a body upon which an electric charge had been built up would attract a nearby uncharged body, but after physical contact had been established the attracted body would be repelled. This action occurs because whenever two such bodies actually touch there immediately takes place an equalization of electronic units resulting in the attracted body becoming charged to the same value of polarity as that of the body which caused the attraction. Finally, when both bodies assume like charges of equal value they repel each other. Also, we observed that a body holding a positive charge on its surface would attract a body with a negative charge and vice versa.

Thus we see nature constantly at work tending at all times to maintain unit masses in a state of equilibrium. Since all matter is essentially electrical in substance, then for any condition where the state of rest is upset, nature will exert her forces to restore normal conditions as quickly as possible.

The fundamental laws of electrostatics may be concisely stated as follows:

1. A field of force, called an electrostatic field, always exists in the region about a charged body or between any two bodies or points where a difference of potential exists. Neither a positive nor negative charge is ever produced alone.
2. Bodies holding charges of electricity of similar kind or similar polarity repel each other.
3. Bodies holding charges of electricity of opposite kind or opposite polarity attract each other.
4. Bodies which have been charged, irrespective of the value of the charge, display an attraction for neutral bodies, that is, bodies which have not been made to exhibit electrical characteristics.
5. An electrical charge can be transferred from one body to any other body (conductors and insulators included) when proper insulation is provided.
6. Electrical or static charges rest only upon the outer surface of a material.

## PROBLEMS ON CHAPTER II

**1.** In a few brief sentences tell what you learned from the electroscope experiment.

**2.** (*a*) State four fundamental laws of electrostatics.
  (*b*) What is an electrostatic field?
  (*c*) Draw a sketch illustrating two charged bodies, one positive and one negative, showing the electrostatic field, using lines and arrows.
  (*d*) Do electrostatic lines exist within a charged body? Explain.
  (*e*) How may an electrostatic field be produced? Mention two ways you know of.

**3.** What is a conductive circuit?

**4.** (*a*) What is an element? (*b*) A molecule? (*c*) A compound?

**5.** (*a*) If the atoms of a certain body (called *M*) contain more electrons than the atoms of another body (called *N*), which body, *M* or *N*, will be charged to the higher potential? And what potential, positive or negative?

(*b*) If we connected a copper wire between body *M* and *N* in (*a*) above, to furnish the electrons a conductive path, then in which direction would they flow, from *M* to *N*, or *N* to *M*?

**6.** (*a*) What do we mean when we say that: A body or mass is in a neutral state?

(*b*) When in a positively charged state?

(*c*) When in a negatively charged state?

**7.** (*a*) What accounts for the differences in materials that enable us to recognize the various things on our earth?

(*b*) Do you think electrical actions could be clearly understood without some knowledge of the electron theory?

**8.** (*a*) Why is it that under certain conditions a body will not show any evidence of electrification although we say that all matter is made up of electricity?

(*b*) According to our modern science, what is a flow of current supposed to be?

**9.** Into what two general classes is electricity divided and what is the principal difference between them?

**10.** (*a*) What is the modern conception of the construction of all matter?

(*b*) What is the name of the theory that is used to explain the reason for all electrical effects?

(*c*) Can an electrical charge of one kind exist alone?

**11.** Name and define four important properties of matter.

**12.** (*a*) If two electrically charged bodies of like polarity are in close proximity will they attract or repel each other? Give reason for your answer.

(*b*) What happens when electrically charged bodies of unlike polarity are within the influence of each other and why?

**13.** (*a*) What is an atom?

(*b*) What is an electron?

**14.** What is your understanding of the terms "positive" and "negative"?

**15.** Explain the meaning of "cohesion" and "adhesion."

**16.** The term "potential" is a word that is very frequently used in this work. How would you explain its meaning to anyone?

# CHAPTER III

# MAGNETISM

## THERE ARE SIMPLE EXPERIMENTS WHICH MAKE IT EASY TO UNDERSTAND THE USE OF THE RELATIVE TERMS, "NORTH" AND "SOUTH" POLES, AND THE CAUSES FOR ATTRACTION AND REPULSION BETWEEN MAGNETIZED SUBSTANCES. ALSO, THE LAWS RELATING TO MAGNETISM ARE EASILY UNDERSTOOD FROM THESE SIMPLE EXPERIMENTS

MANY centuries ago in the mining regions of a small town named Magnesia, in Asia Minor, there was found a dark-colored stone which possessed a very peculiar property—one that could be described as a sort of pulling force—which gave this substance the power to attract small pieces of iron. It was then discovered that if a piece of this stone were suspended by a thread and allowed to move freely it would swing about slowly and, upon coming to rest, would assume a position nearly due North and South. Early mariners used this stone as an aid in navigation, guiding their vessels according to its position, and for this reason the stone became known as "lodestone," which means "leading stone." Another name given to this stone (which is an ore of iron) is "oxide or iron," or "magnetite." The peculiar property we refer to became known as **Magnetism** and the substance itself which possessed the property was called a **Magnet.** The lodestone retains its magnetic properties indefinitely, for it is the result of a *natural* condition within the ore itself.

In later years it was discovered that by an *artificial* process ordinary hard iron, or steel, could be made to take on the same property of magnetism as the lodestone. Thus, the magnetic property imparted to steel gave it the power to attract bits of iron, and, moreover, it was noticed that when a thin strip of magnetized steel was suspended, and permitted a free motion, it would swing about and come to rest in a position exactly similar to the lodestone with regard to the earth's North and South poles. The needle of the common magnetic compass, which is in widespread use, is nothing more than an artificial magnet; it is a magnetized piece of steel suspended so that it can turn freely. As most of us know, one end of the compass needle points in a general direction toward the *North geographical pole* of the earth and the other end points toward the *South geographical pole.* Convention, or custom in the past, accounts for the fact that the North (N) of a needle is so designated and used to identify the location of our North geographical pole only in a general way, as explained in the following paragraph.

In order to avoid any misunderstanding in our study of magnetism, let us explain now that the north end of the needle is actually attracted by the earth's magnetism issuing from the *South magnetic pole.* This magnetic pole is located at a town named Boothia, in Canada, a distance of more than a thousand miles from the North geographical pole. Our earth is really a huge magnet with magnetic forces evident all over its surface, the forces being very pronounced and concentrated at the upper and lower extremities, or, as we would say, "at the poles." Hence, to be strictly accurate in our statement we should say that the "N" end of a compass needle points towards the *South magnetic pole* of the earth and the "S" end towards the *North magnetic pole.*

To make certain that you have a perfect understanding about polarity as indicated by a compass let us look at the conditions this way: Consider that if the north (N) end of the needle points toward a magnetic influence, the region of this influence must be of opposite attraction, or a south (S) pole. If, on the other hand, the south (S) end of the needle points toward a magnetic influence that region must also be opposite, or a north (N) pole.

**Induced Magnetism.**—Figure 23 illustrates the principle of magnetic induction and attraction. When a steel bar magnet is dipped into soft iron filings, it will be found that a large number of the iron particles will cling to one another and to the bar with great tenacity. Most of the filings will cluster near the ends of *the bar with very few distributed along the surface and practically none at or near the middle. The iron particles which are in contact and closest to either end of the bar will seem to grip on* with great firmness whereas those further out from the end are more feebly attracted to one another and seem to be less rigid. This indicates that the magnetism emanating from the ends of the bar is strongest near its surface and, as the magnetism proceeds outward into space, it becomes weaker.

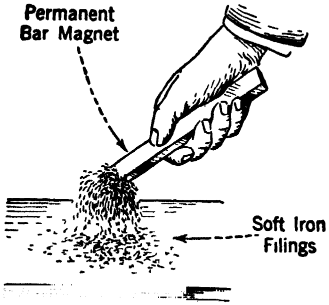


Fig. 23.—An experiment to illustrate the principle of magnetic induction by the action of the magnetic forces surrounding the bar magnet upon the iron filings.

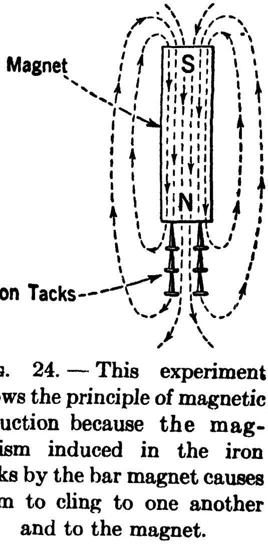


Fig. 24. — This experiment shows the principle of magnetic induction because the magnetism induced in the iron tacks by the bar magnet causes them to cling to one another and to the magnet.

We use the term "density" to express this difference in magnetism, saying that the *magnetic density* is greatest close to the bar. This means simply there is a greater concentration of magnetic force closer to the magnet's poles than at some distance away from them.

If a very strong steel magnet were used to attract the filings, and later you attempt to brush them off with your fingers, it would not prove an easy matter to remove absolutely every tiny iron particle from the magnet's surface. The manner in which these small iron bits cling to one another, and to the bar, indicates that regardless of the exact nature of this magnetic influence its force extends outward into the surrounding space, which is called the "space medium." The iron tacks clinging to the magnet, as shown in Figure 24, also serve to demonstrate the principles of induced magnetism.

The unseen influence around a steel magnet causes each individual filing in Figure 23 to become a tiny magnet possessing all the properties of the large bar magnet itself. We usually express this action by stating that the large magnet *induced* magnetism into the iron filings. The filings would have magnetism induced in them whether they were in actual contact with the magnet or merely in its presence. To prove this statement place the filings in a glass tube or bottle, and then move the magnet against the outer surface of the glass and note how the filings are affected and shift around and cling to one another, assuming different positions according to the magnet's influence. Also, from this experiment, we observe that glass is transparent to a magnetic force. Remember that each filing or tack assumes a position that enables it to accommodate the greatest amount of magnetism coming from the exciting magnet.

**Magnetic Properties Already Exist in Iron.**—The sketches in Figures 23 and 24 are intended to show that *magnetism is not created but already exists in the iron tacks and filings.* Nothing has been added to or taken from the iron to produce the results we observed in these sketches. It is simply a condition where this peculiar force (called magnetism) in the filings or tacks was made evident by the outside magnetic influence of the steel magnet. We know of several practical means for establishing magnetism and, also, ways to regulate its strength. This is a fortunate circumstance, indeed, because it permits us to utilize this invisible force in our radio and electrical work.

Under ordinary conditions if we were to place materials like copper, paper, or wood within the influence of a magnet we would not expect to observe magnetic effects such as the filings gave us in Figure 23. At first sight it might appear that any substance which is seemingly unaffected when subjected to a nearby magnetic force does not possess magnetic properties; but this is not the case. The phenomenon of magnetism exists in all matter to a more or less degree, only in some substances its detection becomes apparent quickly while in others it requires the most diligent research and delicate equipment to discover it. To make it pronounced in paper, wood, and all other so-called non-magnetic substances would require an outside magnetic influence of considerable strength. If conditions were just right and if very strong magnetism was obtainable it could be shown that a piece of paper would be feebly attracted and would move toward the source of strong magnetism, whereas a piece of copper would be repelled.

We deal exclusively with iron and steel in our studies about magnetism because magnetic effects are especially pronounced in these metals, and for magnetic purposes they are the principal ones found in commercial use. However, it should be known that there is a certain compound consisting of iron and a small percentage of nickel that has magnetic properties superior to either iron or nickel alone. "Permalloy" is the name of one compound that can be magnetized about thirty times stronger than soft iron under similar conditions. The best composition of permalloy has a content of 21.5 per cent iron and 78.5 per cent nickel. "Permivar" is the name of another compound which has superior magnetic qualities. Its composition is of the order 45 per cent nickel, 25 per cent cobalt and 30 per cent iron.

**Two Sources of Magnetism in Our Practical Work.**—Let us mention at this point that the magnetic force set up by a fairly strong magnet is not only capable of attracting bits of iron and causing attraction or repulsion with other magnetic masses, but has the additional property of setting up a flow of current through coils, wires, and other elements composing an electric circuit. To produce a flow of current the magnetism which acts on the coils and conducting wires must be made to vary either in strength, or polarity, or both, and the circuit must be closed to form a complete conductive path for the current to flow. Or, if a magnetic force remains stationary and steady, a coil or conductor must be moved through it to produce a current of electricity therein.

It will be shown in a forthcoming chapter that an electric current passing through the turns of a coil sets up its own magnetic lines which completely encircle the coil. The lines set up by the current have qualities precisely similar in every way to magnetic lines produced by either a bar or horseshoe magnet. Bear in mind that magnetism, regardless of how or where it is obtained (either through the use of magnets or from a flow of current), always exhibits the same general properties. Therefore, after having once mastered the fundamental principles outlined in this and the following chapter the student should find it easy to apply them to any action where magnetism and electric current are involved.

From these statements it is seen that there are two principal sources of magnetism:

1. Magnetic effects resulting from the use of magnets.
2. Magnetic effects resulting from the flow of electrical currents.

The first-mentioned source is treated under the topic of **Magnetism** and the second, under **Electromagnetism.**

Just what takes place in the "space medium," or in a "material," when a magnetic force is present, or just what the nature of magnetism is, we do not definitely know. But the results obtained when forces of this kind act upon magnetic substances, or upon conductors of electricity, have enabled scientists to formulate numerous laws and rules governing their behavior.

Very simple experiments can be performed to demonstrate "magnetic" and "electromagnetic" phenomena with a minimum of equipment, as, for example, with the use of a small pocket-size magnetic compass, a bar or horseshoe magnet, iron filings, coils of wire and a battery, or dry cell.

**Kinds of Magnets.**—Magnetic substances are divided into two classes, namely:

(1) Natural magnets, and (2) Artificial magnets.

It should be quite obvious that a lodestone is a natural magnet and that all manufactured or man-made magnets are in the artificial class. The artificial magnets are divided into the following two groups:

(1) Temporary magnets, and (2) Permanent magnets.

Inasmuch as the soft iron filings in Figure 23, or the tacks in Figure 24, lose practically all their magnetism when removed from the magnetizing force, they are classed as temporary magnets. Suppose, on the other hand, that these filings, or tacks, after being shaken free from the bar, were to retain their magnetic properties (assuming that even after a period of many months or perhaps years they still persist in clinging strongly to one another); they would be classed as permanent magnets. Assuming that a solid bar of iron or steel showed properties similar to the tacks and filings, as we have just suggested, the bar would also be called a "temporary" magnet, or "permanent" magnet, as the case may be. The point we wish to emphasize is that the size of a mass does not alter these conditions.

**Types of Magnets.**—There are in general use three types of magnets. The path of the magnetic forces in each type is shown in Figure 25.

(1) Horseshoe magnet. . (Magnetic circuit consists partly of iron and air).
(2) Bar magnet. . . . . . . . (Magnetic circuit consists partly of iron and air).
(3) Ring magnet. . . . . . . (Magnetic circuit consists only of iron.)

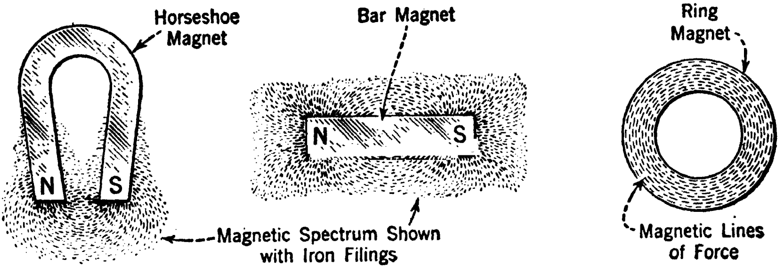


Fig. 25.—Sketches of three typical types of magnets.

**Simple Way to Make a Magnet.**—Suppose that one-half of a bar of hardened iron or steel is repeatedly stroked with the "N" pole of a strong magnet, and each stroke is made the same way, beginning at the middle of the bar and stroking toward one end, then this end of the bar will presently become an "S" pole. Suppose the "S" pole of the magnet is now used to stroke the opposite half of the bar by the same process, then the latter end of the bar will become an "N" pole. If this bar into which magnetism is being induced is hardened iron, and it is heated or slightly pounded during the process, either treatment will assist the molecules in rearranging themselves in parallel rows (or in alignment) to make the bar a permanent magnet. It will be explained in the next chapter, under the subject of "Electromagnetism," how a coil of wire through which current is flowing can be utilized to induce magnetism into a bar of hardened steel to make it a permanent magnet.

**Flux—Magnetic Field—Magnetic Lines of Force.**—To illustrate a "force" on paper is just like attempting to draw something one cannot see. For instance, you could not illustrate your "thinking powers" on paper, nor could you graphically show the "force" of an explosion. With this in mind you will appreciate why it has become the custom merely to draw a line to illustrate the line of direction of a force and then to place an arrow somewhere in that line to denote the exact direction in which the force is being applied. That is, the arrow shows the tension along the line. The magnetic forces which exist within a magnet and in the region surrounding it are, therefore, best illustrated by lines and arrows.

The total magnetic lines of force set up in a magnetic circuit (either by a magnetic material or by an electric current) are called *magnetic flux,* or simply *flux.* The flux is shown by dotted or dashed lines in our drawings. These lines take the form of ever-widening loops which may be thought of as a sort of magnetic whirl.

The field of force which is evident in the region outside a magnet is called the *magnetic field.*

The idea of presenting an unseen force graphically on paper is similar to that used in the preceding chapter on "Electrostatics." The difference is mainly that unbroken lines are drawn in the region where an electrostatic field of force exists, whereas dotted or dashed lines are used to represent a magnetic field of force. Note particularly the formation of the magnetic lines of force in each of the different types of magnets in Figure 25. See how the majority of the lines come out at the region around one pole and go in at the region around the opposite pole, with comparatively few lines at or near the middle of the magnet. Of course, in the case of the ring magnet, the lines are confined entirely within the iron mass because this magnet has no poles; consequently a magnetic spectrum using iron filings cannot be shown as with horseshoe and bar magnets.

**Magnetic Lines of Force Can be Visualized Only by Indirect Observation.**—Magnetic forces cannot be seen, as you know, but their effects can be observed. In order that you may actually visualize the strain lines (lines of force) present about a magnetized substance it is suggested that the following simple experiment be performed. Obtain a small bar magnet or horseshoe magnet, a sheet of cardboard or glass, and a small quantity of soft iron filings. Someone connected with a machine shop in your neighborhood will no doubt give you the filings; a thimbleful or two will be plenty, or you may easily make them by filing part of an iron bolt, or any piece of ordinary iron, for that matter.

Let the bar magnet be placed under the cardboard, or glass, and let the iron filings be sprinkled evenly over the flat surface. Then gently tap the surface a dozen times or more with a pencil and observe how the iron particles actually turn about and arrange themselves in lines or loops in a symmetrical formation, according to the sketches of the horseshoe and bar magnets in Figure 25. The energy in the magnet induces magnetism in the filings, causing each one to become a tiny magnet having its own "N" and "S" poles; it is the *induced magnetism* that makes the filings attract one another, causing them to form loops or whirls.

Each of the lines of force completes an independent circuit, as shown by the continuous loops. The loops (or lines) tend to shorten themselves at all points, that is, they tend to take the shortest route in the space they occupy between opposite poles. However, *the lines remain separated and spread out an infinite distance from the bar because of the strong repulsion which adjacent lines exert on one another. One line never crosses over, cuts through, nor merges into neighboring lines.* See Figures 26 and 27.

The force lines exert a tension in a direction outward from the "N" end of the magnet as they pass around the bar through space and re-enter at the "S" end, the tension being continued on through the bar from "S" to "N," as indicated by the loops and arrows. When speaking about this characteristic of magnetism we say that lines of force are in a direction from "N" to "S" around a magnet and from "S" to "N" inside.

The exception to the foregoing rule is a ring magnet, which forms a closed iron circuit; in this type there are no open ends or poles and therefore the lines are confined within the iron. However, if a section of a ring magnet is cut out, the open ends thus made then become "N" and "S" poles, respectively, with a magnetic field set up in the space between them.

In the action explained in the preceding paragraphs, where the force lines originating in the bar magnet exert their influence on the iron filings and cause their rearrangement, it may be added that this action in turn places the filings in a position so that they exert their individual influences on one another. Keep in mind that each little filing becomes a magnet in this process. Consequently, we have a greater total magnetic force existing in the region around the magnet when filings are present than without filings, because the force lines set up by the filings when they are magnetized *add* to the force lines coming from the bar magnet.

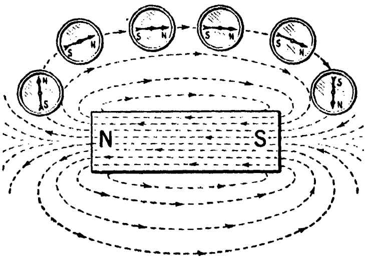


Fig. 26.—Showing how a compass may be used to determine the presence of magnetic lines of force.

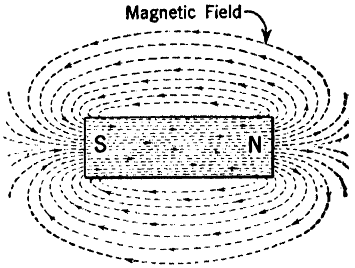


Fig. 27.—Magnetic lines of force take a symmetrical form; they leave the bar magnet at one end, surround it on all sides and re-enter the opposite end as depicted.

**Exploring a Magnetic Field with a Small Compass.**—Suppose we explore the magnetic strain set up in the region about a steel magnet by moving a compass in various positions as suggested in Figure 26. We will see that when the needle comes to rest at some particular location it will take up a definite direction acting along the lines of force at that point. The several positions of the compass in the drawing show that the needle coincides with the lines of force in every case.

Hence, a magnetic compass is useful for detecting the presence of a magnetic field and determining the direction in which the lines run. The diagram of the field about the magnet and the compass in Figure 26 teaches you how to determine the polarity ("N" and "S" poles) of a magnet.

**Magnetic Spectrum.**—In Figure 27 we observe a bar magnet and the region surrounding it placed under a strain by the force lines leaving at points toward one end of the bar and re-entering at similar locations toward the opposite end. This gives a symmetrical appearance to the formation of the lines as mapped out by the iron particles in the bar magnet in Figure 25.

The shape or image of the magnetic lines, as viewed with the *aid of the filings, is called a "magnetic spectrum" as illustrated in the small horseshoe and bar magnet sketches in Figure 25.*

*Since strain lines always exist around a magnet* then for any change made in the position of a magnet the strain lines will move along with it. Try moving the bar magnet in Figure 23 slightly back and forth in different positions and note the effect on the filings.

**The Laws of Attraction and Repulsion.**—

(1) Magnet poles of like kind repel each other.
(2) Magnet poles of unlike kind attract each other.

To prove the laws just stated we will make use of two steel bar magnets whose "N" and "S" poles are known and marked as shown in Figures 28 and 29. One magnet is suspended by a thread so that it will move freely under the influence of the other magnet.

(1) If one of the magnets is held in the hand and slowly moved, as shown in Figure 28, so that its north pole end is brought near the north pole end of the suspended magnet, we will immediately see the latter move away and come to rest in a position as far as possible from the first magnet. This demonstrates the law of *repulsion.*

(2) Now suppose the south pole end of the magnet in the hand is brought near the north pole end of the suspended magnet, as shown in Figure 29, then we will obtain an effect just opposite to the one observed in (1). This time the north end of the suspended magnet will swing toward the south pole of the approaching magnet, with the swinging magnet coming to rest in a position as close as possible to the magnet held in the hand. The ends of the magnets will actually come into contact if you permit them. This demonstrates the law of *attraction.*

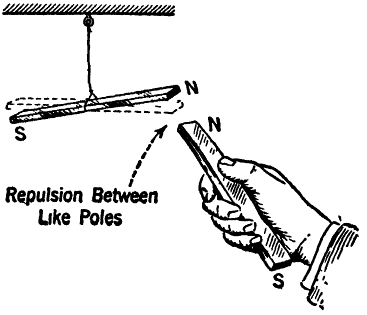


FIG 28—A simple method to demonstrate the law of repulsion.

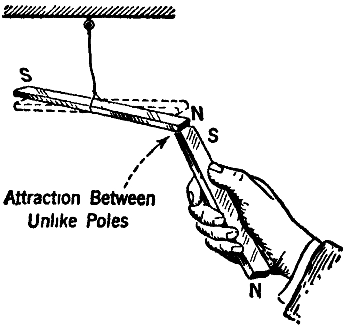


FIG. 29—Unlike poles attract as depicted by this drawing.

Referring to foregoing paragraph (1); the explanation for the action relating to *repulsive effects* will be understood after examining the sketch in Figure 30 and keeping in mind that the magnetic forces act along the lines and in the direction indicated by the arrows. Observe how the lines representing each field are distorted from the normal arrangement they occupy when not under the influence of each other. The shape of a normal field is shown in Figures 26 and 27. A similar effect of repulsion would be produced if two south poles were brought near to each other.

Referring to foregoing paragraph (2); the explanation governing the action relating to *attraction effects* will be understood by an examination of Figure 31 and reasoning as follows: The attraction or pulling effect between adjacent magnetic poles of unlike *kind is caused by the lines coming out from the "N" end of the first magnet and going in at the "S" end of the second magnet, that is, the tension of the lines is acting along the same direction as shown in the drawing*

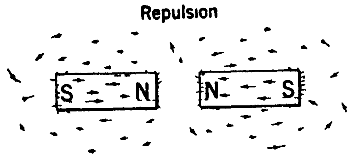


Fig 30—Showing the repulsive effects of lines of force between poles of like polarity Compare this drawing with Figure 28

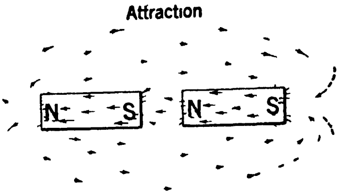


Fig 31 Illustrating the attractive effects of lines of force between poles of unlike polarity Compare this drawing with Figure 29

**Theory of Magnetism is Based on the Energy Stored up in a Molecule and Atom.**—Now, examine the drawings in Figures 32, 33, and 34 for the purpose of studying the molecular action within an iron bar when it is demagnetized, or magnetized, or saturated with magnetism Before we go into a detailed explanation of these drawings let us first mention a few facts about "energy" and the general conception that all magnetic effects in iron are thought to be *due to an alteration in the position the molecules normally occupy* You should, at this point, recall some of the explanations given in Chapter II about the composition of matter You learned that all substances are composed of molecules, and that the molecules in turn consist of atoms, and finally the energy within the atom is a combination of positive and negative electrical forces The negative forces are the rapidly vibrating electrons as previously explained

Our explanations also stated that magnetism and electricity are inseparably associated in all kinds of "matter," and that *energy in different forms is accounted for by the action of electrons in constant motion* It may be of more than passing interest to mention that according to the belief of scientists the many different kinds of substances found on our earth and the energy they possess were produced ages ago when our earth was in the process of cooling and formation

It is quite evident that *energy* already exists in iron and steel molecules and this energy is capable of doing "work" when properly directed. The results of the "work" performed by a magnetic force was observed in Figures 23 and 24 when iron particles and tacks were attracted toward a bar magnet and their weight was supported by it. Also, we saw that magnetic properties, exactly similar to those of the steel magnet itself, were induced in the iron particles. This ability of iron and steel to become magnetized and to do work permits us to consider any material displaying such qualities as a storehouse of energy.

**Use of the Terms Magnetized and Demagnetized—Attraction and Repulsion.**—The power of either attraction or repulsion which one magnetized material exerts upon another was illustrated in the experiment with the bar magnets in Figures 28 and 29. Although these principles have been discussed before, let us again repeat that each bar magnet has a north and south pole and, also, if two like poles, north poles for instance, are brought together, the bars will move away from each other owing to *repulsion*. Two south poles placed in the same neighborhood would also repel each other. On the other hand, if two unlike poles, north and south, are brought together, the bars will move toward one another, and will touch if permitted to do so, owing to *attraction*.

If you obtain some soft iron filings and actually try the experiment previously suggested in Figure 23 you will notice that after the filings are shaken off and removed from the magnet they cease to cling together; as far as all outward signs are concerned they have lost their individual magnetic properties. In other words, just so long as the filings are subjected to the magnetizing influence they continue to remain magnets, but when they are not subjected to this influence they lose practically all their power to attract one another as you observed. In this process the filings were first *magnetized* and then *demagnetized*.

There are certain kinds of iron that, after being magnetized, will retain their magnetism for much longer periods than the soft iron filings which we used. This subject is treated later on under "Retentivity."

**Conditions in a Non-magnetized Iron Bar.**—The energy contained in a magnet that enables it to perform work is stored up in the molecules of the substance, as we have previously explained. Figure 32 is given to show that every molecule (molecules are merely suggested by the reactangles) is a magnet in itself, having its own "N" and "S" poles. If we could actually draw the molecules showing them linked together to form numerous closed and irregular shaped groupings with none of the molecules in adjacent groups in exact alignment, then we could safely say that it would be difficult to detect magnetism in a region external to the bar.

The extreme ends of each molecule are called "poles," and by convention they are known as "north" and "south" poles, respectively. The "N" pole ends are indicated in the sketch by solid black squares and the "S" pole ends by white outlined squares.

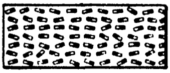


Fig. 32.

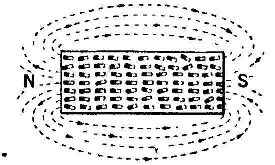


Fig. 33.

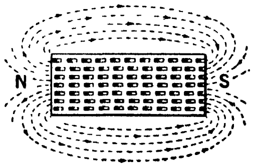


Fig. 34.

Fig. 32.—A means of showing the myriad of molecules which compose an iron bar. Each molecule is a tiny magnet in itself, having a north and a south pole.

Fig. 33.—When an iron bar is magnetized the molecules arrange themselves in more or less parallel rows as depicted in this drawing.

Fig. 34.—The "saturation point" is reached when the molecules in an iron bar are in perfect alignment and its magnetic strength can not then be increased.

There is a natural attraction between neighboring molecules which causes them to arrange themselves in a somewhat irregular order with their north and south poles practically together. When an iron mass is in such condition that its magnetic forces are confined to closed paths by virtue of the closed molecular groups as explained in the second paragraph preceding, the iron will not display any noticeable outward magnetic effects. The iron in this condition is said to be *non-magnetized* or *demagnetized.* In other words, although magnetism is present within the bar, it is not evident in the region outside and, consequently, there is no magnetic field produced.

**Conditions in and around a Magnetized Iron Bar.**—If a piece of soft iron is brought near a steel magnet the iron will become magnetized, as mentioned in an early part of this chapter. The molecules of soft iron, when under the exciting magnet's influence, are thought to be forcibly turned about on their axes and, hence, they rearrange themselves in a manner somewhat like the drawing in Figure 33. They form parallel rows with their "N" and "S" poles lined up end to end.

When this alignment of molecules is brought about, the energy in each molecule adds to that of its neighbor, with the result that the "N" poles point in the same general direction toward one end of the bar and the "S" poles toward the opposite end. Thus, the magnetized iron has all the properties of a magnet, that is, it has a north pole and south pole of its own. We have, then, a condition where the magnetic energy in the molecules now exerts its influence in the region outside the bar, setting up strain lines in this region, the strain lines being called a "magnetic field." As indicated by lines and arrow-heads the force or strain lines about a magnet leave at the north pole and re-enter at the south pole.

The magnetic circuit sketched in Figure 33 consists of air and iron. The air path is technically known as the "space medium." However, in practice you will find that a magnetic circuit may consist of air or iron alone, or a combination of both. Magnetic flux encircling a coil when current flows is an example of a complete air path, whereas a ring magnet, such as the one in Figure 25, is an example of an all-iron path. A ring magnet may be employed where no external field is desired.

From the facts stated heretofore the student should readily grasp the idea that a magnetic force is continuous. However, to make this point positively clear, let us suppose that in Figure 27 there are 100,000,000 lines of force within the bar (we have shown only several strain lines for simplicity); then we would also have 100,000,000 strain lines acting on the space medium. In other words, for each line existing in the bar the space outside is subjected to the strain of one line, for the simple reason that every line is continuous; it has no beginning or end. Moreover, the space about a magnet opposes being placed under a strain and, consequently, it exerts a constant effort to recover its normal state.

It is of utmost importance that the student should think of magnetic flux acting entirely around a magnetic circuit and not that the lines start or end at any particular point

**Conditions in Iron or Steel when Saturated with Magnetism.**—The drawing in Figure 34 shows several rows of perfectly aligned molecules It is only natural to expect that such straight rows of molecules, when exactly end to end, will exert the greatest strain or tension in regions outside the magnet In practice, however, molecules do not as a rule form absolutely straight lines but their rearrangement is more or less imperfect In any event the extent of molecular rearrangement is dependent upon the kind of substance being magnetized and the strength of the inducing force. Each line contributes its individual magnetizing force to the total produced by the magnet. If all the molecules of an iron or steel bar were rearranged as perfectly as those shown in Figure 34, then no further magnetism could be induced in the bar, since there is nothing more than could be done to the iron to make it "take on" or "hold" more magnetism In this condition the iron would be said to have reached the "saturation-point," known as "magnetic saturation" Therefore, its magnetic strength could not be increased beyond this limit, regardless of how strong might be the magnetizing force

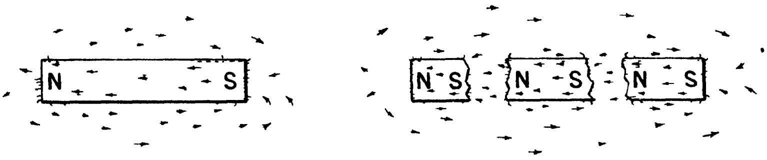


FIG 35 —If the bar magnet on the left is broken into several pieces as shown in the right-hand drawing, each piece becomes a magnet in itself with north and south poles

**Effect of Breaking a Magnet into Smaller Pieces.**—The sketches in Figure 35 are intended to convey the idea that magnetism is due to a certain molecular arrangement and, also, that magnetic lines form a continuous circuit, they cannot be thought of as having any beginning or end. Accordingly, if a bar magnet is broken into several pieces, as illustrated, each piece becomes a separate magnet with "N" and "S" poles of its own and with strain lines established in the surrounding space.

**When Two Magnetic Forces Act Simultaneously in the Same Region.**—The purpose of showing the weather-vane in Figure 36 is to explain by a simple comparison with two air currents what would happen if two independent magnetic fields, established in the same region, acted on each other. Suppose we have the force of one air current, marked *A*, acting in the direction indicated by the arrows, and a second air current, marked *B*, acting from some other direction. If the two currents meet at a place where a weather-vane is erected the vane will move about and finally come to rest pointing in a direction different from either of the oncoming air currents. The final direction assumed by the vane is a *resultant effect* of the two forces acting on each other. So it is with magnetic forces. If two magnetic fields are brought together in the same region the fields will be distorted, and the final direction of the magnetic lines, or the resultant field, will be governed by the angle at which the fields meet and the relative strength of the forces acting.

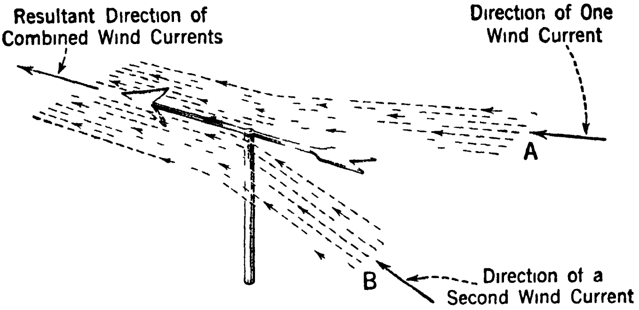

Resultant Direction of Combined Wind Currents
Direction of One Wind Current
A
B
Direction of a Second Wind Current

FIG 36.—A weather vane analogy to show the resultant effect when two forces act on each other

**Hysteresis—Molecular Friction.**—That molecules of iron actually do move and turn about on their axes when brought into the presence of a magnetic force can be proven in a practical way. If a magnetic force acting on an iron bar changes continuously in strength, or polarity, the iron molecules composing the bar will rearrange their positions in accordance with the changing force. The molecules, as they shift slightly back and forth, rub one another, and in so doing they generate heat in the iron. The heat developed in the iron or steel parts of any electrical apparatus, which is built to function only when subjected to rapid changes in magnetism, represents one source of energy loss.

Therefore, if we wholly or partially magnetize and demagnetize a piece of iron steadily for a given length of time, which we can do by various means, the iron will become warm and under certain conditions it may even become very hot. The heat is said to be due to *molecular friction* between the iron particles, and all this happens despite the fact that we can see nothing of the invisible forces that are acting. It is obvious that heat is a waste of energy when it is not desired, or when it is not put to some useful purpose.

It is more difficult and requires greater magnetic influence to alter the molecular arrangement of steel than iron, that is to say, steel naturally resists being magnetized or demagnetized to a greater extent than iron. The energy loss that occurs in iron or steel when subjected to rapid changes in their molecular arrangements is called "hysteresis."

**Reluctance Explained by Placing a Bar of Soft Iron between Two Steel Magnets.**—The opposition which air, or iron, or any material used in a magnetic circuit presents to magnetic flux is called "reluctance." It will be recalled that in the case of an electrical circuit the opposition to current flow is spoken of as "resistance."

The reluctance of air is about a thousand times as great as the reluctance of ordinary iron. The fact that the reluctance of iron and steel is lower than air explains why lines of force will always take an iron or steel path in preference to an air path. Refer to Figures 37 and 38, which show that when a bar of unmagnetized soft iron is placed between two steel magnets a greater number of lines of force will be accommodated in the iron and a stronger flux will be set up in the magnetic circuit than would be the case if we simply had an air space separating the two steel magnets. The shape of the magnetic fields of the two magnets is normal when the iron bar is removed, as Figure 37 shows. However, when the iron is inserted between the magnets, as shown in Figure 38, their fields are distorted and the lines seek the path through the iron rather than through the air.

So long as the iron bar is kept in the presence of the steel magnets the iron will have magnetism induced in it and therefore will remain a magnet having "N" and "S" poles of its own. The polarity is due to the iron molecules being forced into alignment, a condition similar to that pictured in Figure 33. Note for one thing how the magnetic circuit in Figure 38 is formed and, also, that there is attraction between the three bars since their unlike poles are near each other.

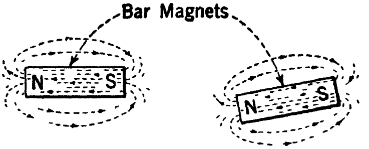


FIG. 37.—When two steel magnets are separated by air only, their fields are normal, as depicted in this sketch.

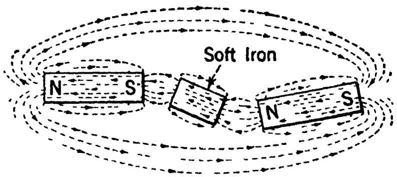


FIG. 38.—When a bar of soft iron is inserted between two steel magnets the fields of the magnets are distorted and the lines of force seek a path through the iron bar.

By moving the three bars closer together shorter air gaps will separate them and, of course, the reluctance of the complete magnetic circuit will be lowered accordingly, with the result that more lines of force will be established. This will increase the attraction existing between the three bars and make the iron bar a stronger magnet. If, on the other hand, the three bars are moved farther apart, the reluctance of the entire magnetic circuit will be increased, owing to the wider air gaps, with the result that less lines will be established, and the iron bar will become a weaker magnet.

In order to understand the reason for the results obtained in Figures 37 and 38 it is only necessary to bear in mind that air offers an infinite opposition to the setting up of magnetic lines, whereas iron naturally offers an easier path for lines of force. This is why iron is attracted to a magnet.

The reluctance of a magnetic circuit is dependent upon the following three factors: (1) the length of the complete magnetic path or circuit; (2) the cross-sectional area of the circuit; and (3) the permeability of the circuit, which varies according to the materials used and the length of any air gaps or spaces present through which lines of force must pass.

**Retentivity—Permeability.**—The term "retentivity" is used to denote the power of substances to retain or hold the greater part of magnetism imparted to them. The term retentivity should not be confused with permeability. The term "permeability" expresses the quality of a material that permits it to become strongly magnetized, or, in other words, it indicates the ease with which a magnetic substance can be magnetized irrespective of how long the substance may retain magnetic properties afterwards.

A piece of hardened steel resists being magnetized, but after magnetism is once induced in the steel it will hold or retain this property for comparatively long periods. It requires a great magnetizing force (called coercive force) to completely demagnetize a steel magnet, that is to say, to return its molecules to such a position or arrangement that the steel will no longer show magnetic properties. So we find that molecules of steel are not easily moved out of their aligned positions after they once assume a certain arrangement. For this reason, steel is used in the manufacture of *permanent magnets.* A permanent magnet should always be handled with care; if dropped or subjected to shocks, jars, or heat, it is likely to lose a considerable part of its magnetism because of the breaking up of the molecular alignment.

On the other hand, soft iron is used where a *temporary magnet* is required because the molecules of this material will arrange and re-arrange themselves with comparative ease when placed in and out of the influence of an outside magnetic force. It should now be apparent that soft iron acts as a magnet only at such times as a magnetizing force is present.

**Density.**—It stands to reason that far more parallel rows of molecules can be packed into a given mass of iron when molecules form exactly straight lines and the lines are very close together, as in Figure 34, than in the case where the molecules are more or less haphazard and partly in alignment, as in Figure 33.

The number of lines that can be crowded into a given magnet determines its magnetic strength, the number of lines per unit area being known as the *density*. The strain at any point near a magnet is indicated by the density of the lines at that point. It then follows that a magnetic field of high density possesses great strength and is capable of doing considerable work, whereas a field of lower density will be comparatively weaker.

**Residual Magnetism.**—If an iron mass, after being subjected to a magnetizing influence, is removed from the exciting force and the iron then holds a perceptible amount of magnetism, the remaining magnetism is known as "residual magnetism." This means simply that the molecules do not all move back into the original positions they occupied before magnetization took place, but a certain number remain permanently fixed in more or less irregular lines, which produces a weak magnetism. "Remanance" is a term used when comparing the total number of lines of force of residual magnetism remaining in different kinds of iron and steel after the removal of the magnetizing force.

**Magnetic Shield—Air and Space Medium.**—We do not really consider *air* as the *space medium* in which magnetic lines are established around a magnet although the term *air* is frequently used to denote this empty region. Just what the medium is has never been ascertained, but it is known that it is something other than air. For instance, suppose we exhaust the air from a sealed glass chamber and have a compass occupy a position in the very center of the vacuous space. It would be found that if a steel magnet were brought near the chamber the magnetic lines emanating from the magnet would penetrate through both the glass wall and the vacuum and cause the compass needle to deflect.

It is interesting to note from this test that neither glass nor a vacuum will act as a shield to block magnetism. Iron is used in practically all cases where a magnetic shield is desired. The principle of an iron shield is as follows: Magnetic lines from some source will not pass directly through and out on the opposite side of an iron shield, but rather the force of the lines acts on the iron molecules tending to re-arrange them and make the shield itself a magnet. What happens is this: the shield takes up the magnetism and in this way shunts the magnetic forces around the region which is to be protected or isolated from magnetic effects. Thus, when a shield is employed, magnetic lines cannot spread outward indefinitely into space, as the lines naturally would do otherwise. The principle explained here is one of *magnetic induction*, and it holds true in the case of any magnetic force acting on iron which tends to make the iron a magnet.

## PROBLEMS ON CHAPTER III

**1.** Explain in a few words the meaning of each of the following terms:
(*a*) permeability (*c*) reluctance (*e*) residual magnetism
(*b*) retentivity (*d*) magnetic saturation (*f*) hysteresis

**2.** Why should a permanent magnet be handled with the greatest care?

**3.** What is the effect of breaking a steel magnet bar into small pieces?

**4.** Name three types of magnets and draw a simple sketch of each.

**5.** Draw a diagram of the magnetic spectrum of a horseshoe magnet.

**6.** Answer briefly:
(*a*) What is induced magnetism?
(*b*) What does the term "density" mean?
(*c*) What does the term "flux" mean?
(*d*) What is a magnetic field?

**7.** What is the molecular condition in an iron or steel bar:
(*a*) When demagnetized?
(*b*) When magnetized?
(*c*) When saturated with magnetism?

**8.** What material would you use to make:
(*a*) A permanent magnet? Why? (*b*) A temporary magnet? Why?

**9.** Name a few of the characteristics of lines of force.

**10.** Explain the laws of attraction and repulsion. How could you easily demonstrate these laws to someone?

**11.** What names do we give the locations on our earth toward which the north and south poles of a compass needle point? Be sure to make your answer clear.

**12.** (*a*) Explain the meaning of "molecular friction."
(*b*) What is the purpose of a magnetic shield?

**13.** Draw a sketch of two bar magnets with their opposite poles facing each other and spaced sufficiently to allow a small bar of soft iron to be placed between the adjacent poles. Now draw in the soft iron bar and with dashed lines show the arrangement of the magnetic lines in this magnetic circuit.

**14.** Explain why the magnetic lines occupy the positions you have shown in your sketch in answer to Question 13.

**15.** Why do magnetic lines remain separated from one another and spread out to form the magnetic spectrum as indicated on drawings given in this chapter?

## CHAPTER IV

## ELECTROMAGNETISM—ELECTROMAGNETIC INDUCTION

WITHOUT THE DISCOVERY OF THE PRINCIPLES OF ELECTROMAGNETIC INDUCTION BY MICHAEL FARADAY IT IS QUITE CERTAIN THAT OUR ELECTRICAL AND RADIO INDUSTRIES COULD NOT HAVE REACHED THEIR PRESENT STATE OF DEVELOPMENT

**A Flow of Current Produces Magnetic Effects.**—The rules and characteristics relating to magnetic lines of force produced by a steel magnet may be applied to all cases where lines of force are produced by an electric current. *Magnetic effects are always set up in the region surrounding a flow of current.* A stream of negative electrons moving from one place to another through any path which acts as a conducting medium is considered to be a flow of current; this is in accordance with the "Electron Theory." Thus a movement of electrons, or current flow, through a conductor (a wire for example) sets up about that conductor magnetic lines of force, forming a magnetic whirl which begins at the center of the wire and extends an infinite distance outward into space.

The magnetic field, or whirl, can be detected easily by means of a magnetic compass, or with the aid of iron filings, as shown by the experiment in Figure 39. It is seen that a wire of suitable length (either insulated or bare wire) is thrust vertically through the center of a sheet of cardboard upon which is sprinkled a thin uniform layer of soft iron filings. The two ends of the wire are connected to the positive (+) and negative (−) terminals of a dry cell which furnishes the electromotive force necessary to send current through the wire. The direction of current flow is indicated by arrows. With current flowing the cardboard is tapped lightly, which causes the filings to move and arrange themselves in concentric circles, each circle being a line of force. Of course, the filings cannot clearly map out all of the lines because of their vast numbers. An important fact to be remembered is that the lines of force exert their effort in a certain direction around the wire and at right angles to it.

Our experiment offers a convenient means for indirectly observing how the passage of current through a wire sets up magnetic effects. Although these whirls of magnetic lines exist along the entire length of the wire circuit (whenever current flows) we are visualizing them at only one location on the wire, i.e., at the point where our cardboard is placed. To prove that the magnetism exists all along the wire move the cardboard up and down, at the same time observing the behavior of the filings. The total number of lines encircling the wire is an indication of the magnetic field strength, or density, and in this case is chiefly dependent upon the number of amperes of current flowing. A current of low value will produce a comparatively weak field, whereas a current of larger value will produce a relatively stronger field. The magnetic lines (or flux) around the wire have precisely every quality possessed by lines existing about a steel magnet. The lines act upon the space medium about the wire to place it under a strain as any magnetic flux would do.

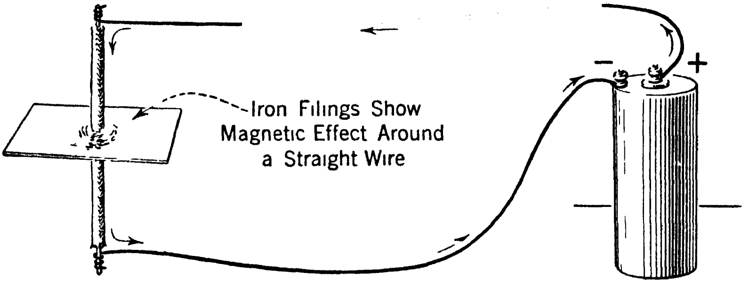


FIG. 39. A simple experiment to detect the magnetic field around a conductor through which current is flowing

**The Magnetic Effect about a "Loop" of Wire when Current Flows.**—Now let us bend the straight wire in Figure 39 into a loop as in Figure 40. It is seen that the magnetic lines are present, but by forming a loop we have obtained a condition where the directions of the lines are all upward inside the loop and all downward outside the loop. Stating this in a different way we could say that all the lines set up by the current emerge from one end of the loop, surround the loop, and re-enter at the opposite end, with the result that a continuous magnetic flux encircles the single turn of wire. Figure 41 shows the magnetic flux set up by current flowing through a coil. The magnetic whirl around each turn is similar to the single turn in Figure 40, but by the coil arrangement the lines around one turn combine with those of an adjacent turn, and so on, throughout the length of the coil. This results in the lines assuming a similar direction around the coil and through the core, that is, they emerge at one end and after continuing around the coil re-enter at the opposite end. Thus, a coil can be made to produce strong magnetic effects because the lines set up by each of its turns add up collectively.

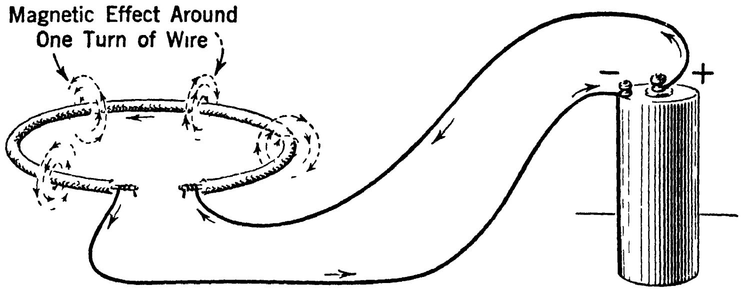


Fig. 40.—This experiment enables us to visualize the magnetic effect around a turn or loop of wire when current is flowing

You should now see from the drawing in Figure 41 that a coil through which current is flowing is similar to a steel magnet in that both produce a magnetic flux and, consequently, both have "N" and "S" poles at their opposite ends. Since magnetic lines of force always have similar characteristics, regardless of how they are produced, then any effects or work which a bar or other type magnet is capable of doing could likewise be done by any suitable coil of wire when current flows through its turns. The following important facts concerning a current-carrying coil should be remembered: (1) The current produces a magnetic flux; (2) the coil has definite "N" and "S" poles; (3) the end of the coil from which the lines of force leave is the "N" pole and the opposite end where they re-enter is the "S" pole.

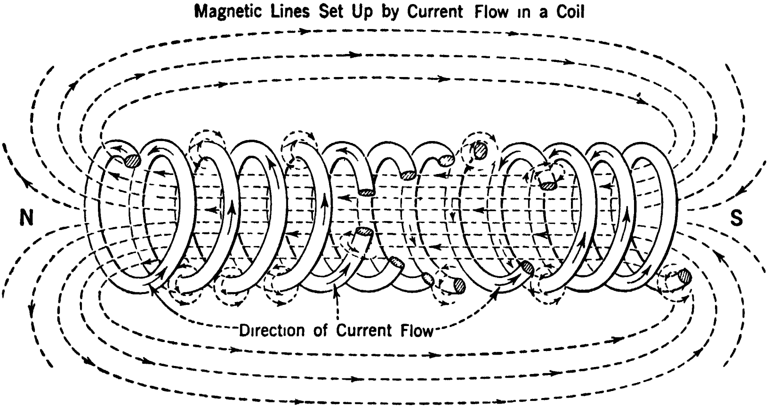

Magnetic Lines Set Up by Current Flow in a Coil
N
S
Direction of Current Flow

FIG. 41.—A coil through which current flows acts similar to a magnet; it produces magnetic flux and has "N" and "S" poles at opposite ends.

**Relation between Direction of Current Flow and Magnetic Lines around a Wire.**—The relation between the direction of current flow through a straight wire and the direction of the lines as they encircle it at right angles can be easily understood by the student after examining the diagram in Figure 42 and applying the following right-hand thumb rule:

> **First Right-Hand Thumb Rule:** If a conductor is grasped with the right hand, with the thumb pointing in the direction of the current flow, the fingers will encircle the wire in a direction similar to that taken by the lines of force. In other words, the fingers coincide with the *direction of tension* which the lines set up in space.

By placing a compass first above and then below a wire when current is flowing, the direction of the force lines can be determined since they exist entirely around the wire in concentric circles. We have shown in Figure 42 how the compass needle points in a certain direction when it occupies a position over the wire, but when under the wire the needle points in the opposite direction. If we were to reverse the connections at the dry cell and cause current to flow through the wire in an opposite direction to that shown by the arrows, the compass needle would indicate this change, since it would point in directions just the contrary to those indicated for positions above and below the wire during the original connection.

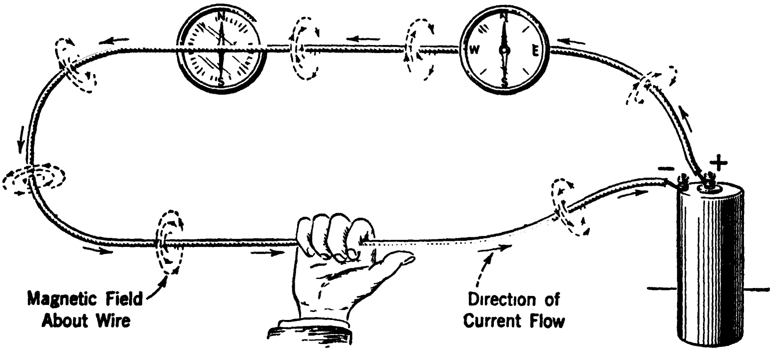


FIG. 42—Applying the "First" Right-hand Thumb Rule to determine the direction of lines of force when current flows through a conductor.

The drawings in Figures 43 and 44 are almost self-explanatory. Figure 43 gives the end view of a wire with the current flowing through it in a direction away from the reader (indicated by a cross) and the lines of force are in a clockwise direction about the wire. Figure 44 shows the same wire with the current reversed and flowing toward the reader (indicated by a heavy dot) and the lines are in a counter-clockwise direction about the wire. Figure 41 illustrates a coil with a cutaway section permitting you readily to visualize the magnetic effects around each turn and the total flux in and around a coil when current flows, as previously mentioned.

The *attraction* between the magnetic fields set up by two parallel wires when the current flows through each one in the same direction is shown in Figure 45. The *repulsion* between two such fields when current flows in each wire in opposite directions is shown in Figure 46.

A close study of Figures 43, 44, 45 and 46 will reveal why magnetic lines produce attractive and repulsive effects.

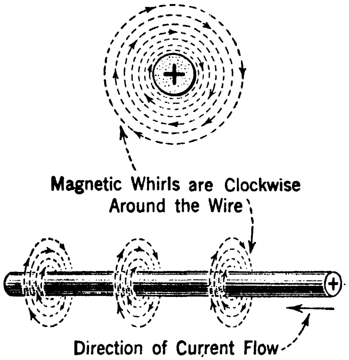


FIG. 43.—Showing the end view of a wire with current flowing through it in a direction away from the reader. Note the direction of the magnetic lines.

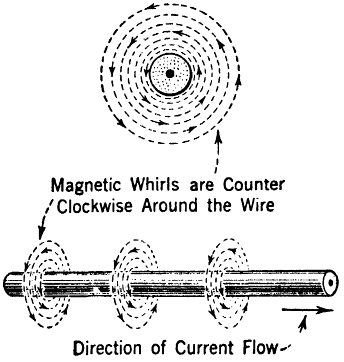

Magnetic Whirls are Counter
Clockwise Around the Wire
Direction of Current Flow

FIG. 44.—The end view of a wire with current flowing through it in a direction toward the reader. The direction of the magnetic lines is clearly shown.

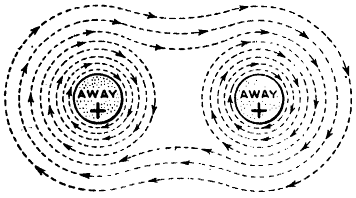


FIG. 45.— Showing why *attraction* is set up between the magnetic fields of two parallel conductors when current flows through each conductor in the *same* direction.

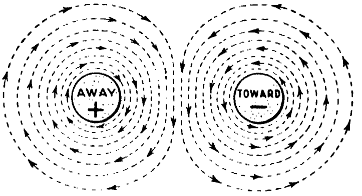


FIG. 46.—Showing the *repulsion* resulting between the magnetic fields of two parallel conductors when current flows through each one in opposite directions.

**Relation between Direction of Current Flow and Polarity of a Coil.**—The purpose of Figure 47 is to demonstrate how you could find the "N" and "S" poles of a coil providing you knew the direction of the current flow. This could be stated otherwise by saying that if you knew the polarity of a coil you could find the direction in which the current passes through its turns. The polarity is determined by applying what is popularly known as the second right-hand thumb rule, as follows:

**Second Right-Hand Thumb Rule: To Determine Polarity of a Current-Carrying Coil:** Grasp the coil with the right hand, place the fingers parallel with the turns, point them in the direction of the current flow, and the thumb will point toward the "N" pole of the coil.

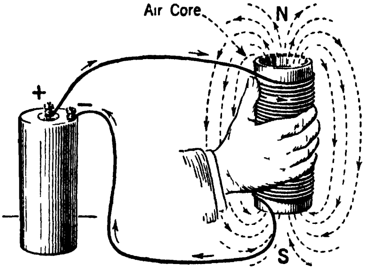


FIG. 47.—A simple means to determine polarity by applying the "Second" Right-hand Thumb Rule. The inside of this coil consists of only an air space and is therefore said to have an air core.

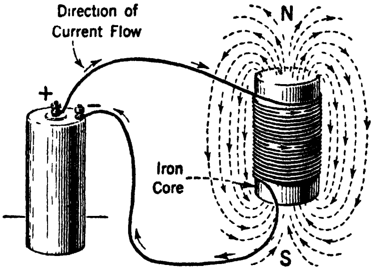


FIG. 48.—When a bar of iron is placed in a coil as illustrated in this drawing the coil is said to have an iron core and the entire unit is called an electromagnet.

**Solenoid—Helix.**—If a coil consists of but a few turns of wire it is usually called a helix (meaning spiral shaped), but a coil wound with a considerable number of turns is more often called a solenoid. In ordinary conversation coils are frequently referred to as "windings."

**Air Core and Iron Core.**—When the inside of any coil consists merely of an air space the coil is said to have an *air core*, like the one in Figure 47. But, if we insert a bar of soft iron into the coil to fill the air space, as in Figure 48, the coil is then said to have an *iron core* and the whole unit is given the name "electromagnet."

**Meaning of "Ampere-Turns."**—The magnetizing effect of a solenoid, or the number of lines of force produced by a given solenoid, are expressions which mean practically the same thing. The number of lines depends mainly upon two factors, namely: (1) the value of the current in amperes flowing through a winding and (2) the number of turns of wire comprising a winding. Hence, the term "ampere-turns" represents the product of the number of turns of wire on a coil and the number of amperes flowing in each turn. We can set down this relation for *ampere-turns* in a formula, thus:

AMPERE-TURNS = AMPERES × NUMBER OF TURNS

According to this formula a current of .2 ampere flowing through a coil consisting of 500 turns will produce exactly the same amount of magnetic strength as will a current of 20 amperes flowing through a similarly formed coil but which has only 5 turns. In both cases we have 100 ampere-turns.

**Electromagnet.**—When current flows through the windings of an electromagnet the iron used in the core becomes magnetized by induction the same as would any mass of iron if brought into the presence of a magnetizing force. When the iron molecules are arranged in parallel rows the iron core itself sets up its own force lines and the latter are added to the lines established by the current in the coil. Thus, in any electromagnet, the magnetic field strength is the sum of the lines set up by the iron core and those set up by the coil. By employing an iron core, as in Figure 48, the magnetic flux set up around a particular coil by a certain current is multiplied many times over that of a similar coil with an air core.

When iron is used and the iron protrudes beyond the ends of the coil it will be noticed that most of the lines pass entirely through the iron before they emerge from the iron and act on the surrounding space medium. However, in the case of a coil with an air core the lines begin to spread out into space at the opposite ends of the coil itself, or where the turns end. This is due to the fact that iron has a higher permeability than air. See Figures 47 and 48.

An example of how powerful an electromagnet can be made is given in the drawing in Figure 49, showing a modern lifting magnet moving large pieces of iron. The large pieces of iron are lifted by means of the strong magnetism produced when a very high current, perhaps 50 amperes or more, flows through coils consisting of a few thousand turns. A magnet of this kind often weighs over 5000 lbs. itself, has over 100,000 ampere-turns, and is capable of lifting iron pieces weighing thousands of pounds. By discontinuing the current in the coils the magnetism drops out of the lifting magnet and the iron pieces are automatically released. The telegraph sounder in Figure 50 is another example of how the properties of an electromagnet are utilized to actuate an iron armature which produces clicks that may be interpreted into the characters forming the telegraph code. Keep in mind that the strength of an electromagnet or any current-carrying coil depends mainly upon its ampere-turns.

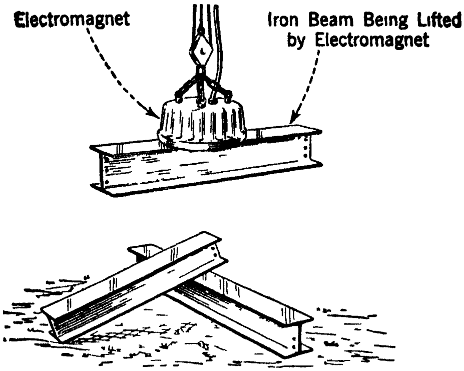

Electromagnet
Iron Beam Being Lifted by Electromagnet

Fig. 49 — Illustrating the work that may be performed by huge and powerful electromagnets

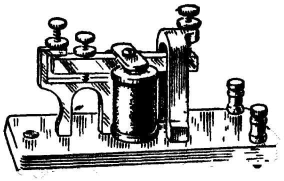


Fig 50 — The properties of an electromagnet are used to actuate the iron armature of the ordinary telegraph sounder to produce the "clicks" that form the Morse code.

**Magnetomotive Force** (Abbreviated m.m.f.).—This is the name given to the unseen force which is accountable for the setting up of magnetic flux in a magnetic circuit. This force is necessary before magnetism can be established, in just the same way that electromotive force is required before current will flow in an electric circuit. There is a certain relation between flux and magnetomotive force. For example, when iron is magnetized and demagnetized part of the work necessary to arrange the molecules is converted into heat, owing to molecular friction. The movement of the molecules, however, lags behind the force in either case. This lag of molecular arrangement is known as "hysteresis." It is always present in iron when used in any circuit where the current varies continuously, as in an alternating-current circuit.

**Summary.**—The important facts to be remembered from the subject of "Electromagnetism," in addition to the two "right-hand thumb rules," are as follows:

(1) A magnetic field is always established in the region around a wire carrying a current of electricity.

(2) When current passes through a coil of wire each turn produces lines. Those lines extending further out from a given turn combine with the lines of neighboring turns to set up a magnetic flux encircling the entire coil. This effect is clearly shown in Figures 41 and 45.

(3) A current-carrying coil exhibits "N" and "S" poles at its opposite ends, since a magnetic field is established in the surrounding space.

(4) A bar magnet and a coil through which current is passing produce similar magnetic effects.

## ELECTROMAGNETIC INDUCTION

**Electromotive Force and Current Induced in Wires by Lines of Magnetic Force.**— We learned in the earlier part of this chapter that an electric current moving through a wire, or any conductor, sets up a magnetic field surrounding the wire, and, also that the lines of force comprising the field reach out a considerable distance into space. The extent or magnitude (called density) of the field about a current-carrying wire depends mainly upon the strength of the current for which the lines are responsible and, also, upon the material of the magnetic circuit, i.e., whether it is all air or partly iron. Other facts brought out were that if a conductor is wound in the form of a coil (helix or solenoid) it produces a magnetic field similar to that of a permanent bar magnet when current passes through the turns of the coil, and that the coil will exhibit north and south poles at its opposite ends according to the direction of the current in the turns. We will repeatedly make use of these facts throughout our present discussion. However, we must now become familiar with principles which are the converse of the above statements, that is, *magnetic lines of force are capable of producing a movement of electric current in conductors under certain conditions.*

It was Michael Faraday who made this discovery, which is one of the most important in all radio and electrical science because from the application of these principles have sprung many forms of radio and power apparatus, such as generators, transformers, and so on. During one of his experiments he noticed that when a conductor was moved through a magnetic field in such a way that it cut across the lines of force an *electrical pressure (e.m.f.) would be set up along the conductor, i.e., induced in the conductor.* That an e.m.f. or electric charge was made available was proved by attaching the conductor to the gold leaves of an electroscope and observing the movement of the leaves while the conductor was being moved. He also observed that if a conductor in which an e.m.f. was induced formed part of a closed electric circuit the induced e.m.f. would cause a movement of current through the entire circuit. "Induced e.m.f." is often called "induced voltage." Let us explain in regard to these statements that *an e.m.f. is induced in an open conductor* (this means a conductor whose ends are left free or disconnected) when acted upon by lines of magnetic force, whereas *an e.m.f. and current are induced in a closed conductor* under similar conditions. When discussing the action occurring in a closed conductor we refer sometimes only to the *induced current,* keeping in mind, however, that we must first have the induced electromotive force.

Among several effects observed by Faraday one was that if a conductor, after being placed in a magnetic field, remained at rest (that is, the conductor was not moved with respect to the lines of force) no induced e.m.f. could be obtained. Nor could an induced e.m.f. be obtained if the conductor was moved in the magnetic field in such a way that its direction of motion was parallel to the direction of the lines of force. In other words, in the latter motion the conductor would *not cut or pass through* the field, it would merely travel along and coincide with the direction of the lines. But he found that if a conductor remained in a stationary position and the magnetic lines were made to move so that they passed through or cut across the conductor an e.m.f. would be induced in the wire under such conditions.

Notice particularly that in all cases involving induced e.m.f. and current we have to consider the relative motion of the conductor and the magnetic lines since either may remain stationary. That is, we must take into account the following conditions, namely: (1) whether a conductor is moved through a stationary field, or (2) whether magnetic lines move past or cut across a stationary conductor.

The foregoing statements form the basis of the study of "Electromagnetic Induction." As we now see, this subject deals with the production of electrical pressures and currents in conductors by making practical use of the invisible force that is always present in the space where a magnetic field exists.

**Current Induced in a Conductor by a Magnet and an Electromagnet.**—In the following explanations it will be shown that the principles of electromagnetic induction remain the same regardless of the source of the flux. The flux may be obtained from the use of a permanent magnet, as in Figure 51, or from an electromagnet, as in Figure 52. In our practical work we find coils of both the air-core and iron-core type in use. The design of a coil is governed by its particular function in the circuit. We do not know, however, that when iron is used for the core material it sets up a magnetic

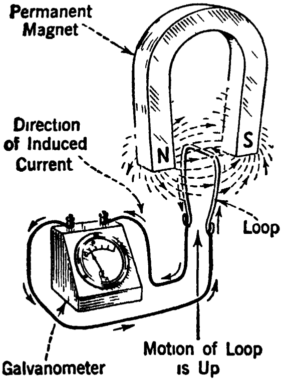


FIG. 51.—By the use of a permanent magnet, a loop conductor and a galvanometer it can be shown that the principles of electromagnetic induction remain the same regardless of the source of the flux.

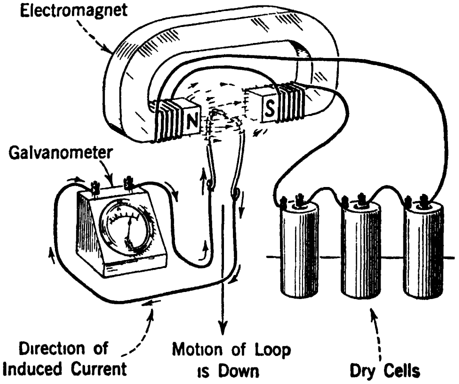


FIG. 52.—An electromagnet is used here to show that the principles of electromagnetic induction remain the same regardless of the source of the flux.

flux which is hundreds of times greater than could be obtained from a given coil when operated with only an air core.

In the experiments in Figures 51 and 52 the induced e.m.f.'s and currents for movements of the loop of wire will be detected by the deflections of the pointer of a sensitive galvanometer. Before continuing with our subject let us first give a brief explanation of this instrument. It consists of a small movable coil carrying a pointer, the coil being mounted on a bearing and placed in the magnetic field of a horseshoe-type magnet; it operates on the principle that a passage of current through the coil causes it to rotate, one way or the other, owing to the force of the magnetism set up by the current in the coil acting upon the force of the magnetism of the magnet. A spring holds the coil and pointer in a zero, or center position. The pointer will move right or left of the zero mark according to the direction of the current supplied to the coil through the connections at the two binding posts on the top of the meter case. The amount of the pointer deflection is taken as the measure of the strength of the current induced in the circuit when the loop of wire moves across the lines of force as illustrated.

Let us now proceed with the experiments in Figures 51 and 52. If the loop is suddenly moved vertically downward a deflection of the galvanometer pointer will occur, indicating that current *momentarily* flows through the closed circuit consisting of the loop, the coil in the galvanometer, and the connecting wires. The pointer will move a certain distance across the scale and immediately drop back to its natural position of rest. Assume that the pointer moves to the right. If the loop is suddenly moved upward the pointer will *momentarily* deflect in a direction opposite to its first movement and, accordingly, it will move a certain distance across the scale to the left of zero. It is evident that when the loop stops cutting the lines the induced current dies out. Bear in mind that the induced electromotive force is generated only *momentarily*, or while the conductor is actually moving and cutting lines.

The galvanometer readings indicate that the induced current in the loop alternates with each reversal of its movement through the field. If the loop is moved quickly across the lines a higher deflection will be read on the galvanometer than if only moved slowly. Also, if instead of moving the loop perpendicular to the direction of the lines we now move it from left to right, or right to left, either way (that is, parallel to the direction of the lines) no lines will be cut and no e.m.f. or current will be obtained. A person performing an experiment of this kind could easily move the loop up and down so rapidly that the pointer, because of its weight, could not follow the variations or reversals of the induced current and, therefore, the pointer would remain at zero, or possibly it might make a slight quivering motion without giving any definite reading.

There are two more important points to be mentioned in regard to Figures 51 and 52. If the loop is held stationary and either the magnet or electromagnet is moved up and down so that the *lines are made to cut through the loop* the same results will be obtained as for conditions outlined in the foregoing paragraphs where the *loop is made to cut through the lines.* And if the magnetic fields were reversed, with "N" to the right and "S" to the left, the induced pressures would then be set up in the reverse directions for the same motions of the loop relative to the field.

**Fleming's Rule for Determining the Direction of Induced E.M.F. in a Conductor.**—To explain the rule it is best to perform the experiments in Figures 53 and 54 with a straight copper rod. It is easy to understand the inductive effects set up in a rod and then later you can apply the same rule to any number of conductors, or turns of wire. A galvanometer is again used to indicate the strength and direction of the induced current, the instrument being shown connected to the ends of rod *AB*.

The laws relating to the direction of the e.m.f. induced in a conductor when it cuts through a magnetic field must be learned in order to understand the principles of the electric generator. The sketches in Figures 53 and 54 are drawn expressly to illustrate one method for determining the relation between the direction of the induced current, the direction of the motion of the conductor, and the direction of the lines of force. In the following paragraphs we will consider two cases: (1) the effect when the rod is moving downward; (2) the effect when the rod is moving upward.

*Case* (1). *If rod* AB *is moved down across the magnetic flux,* as in Figure 53, the induced pressure in $AB$ will be in the direction from $B$ to $A$, as indicated by the arrow alongside the rod. This e.m.f. sends current through the rod and the galvanometer coil and, thus, a momentary deflection of the pointer is seen. Let us assume that the pointer moves to the left of zero and drops back immediately.

*Case* (2). Now, if rod $AB$ is moved up across the flux, as in Figure 54, the induced e.m.f. will be set up in the opposite direction, or from $A$ to $B$, as indicated by the arrow drawn alongside the rod.

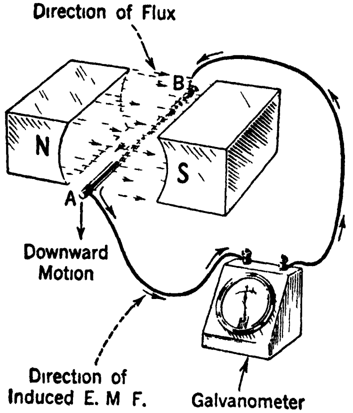


FIG 53.—This sketch shows that a relation exists between direction of induced current, direction of motion of the conductor, and direction of lines of force.

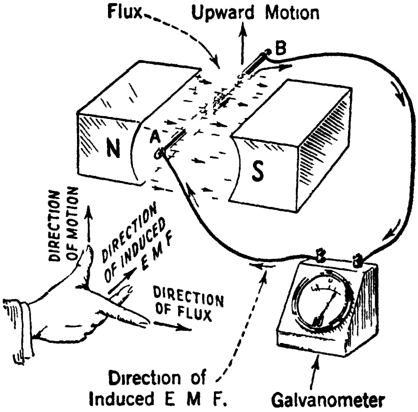


FIG 54 —This sketch shows how to apply Fleming's Right-hand Rule to find the direction of induced e m f.

This reversal of induced pressure with a reversed movement of the rod sends current through the rod and galvanometer coil in the opposite direction to that obtained during the down movement as in Case (1) above. During the up movement of the rod the pointer will deflect momentarily to the right and return to zero.

Hence, we find that the direction of the induced electromotive force depends upon the direction of the lines of force and the direction of motion of the conductor with respect to the lines. An easy way for remembering these relative directions and particularly *to find the direction of the induced e.m.f.* is to apply a rule, known as *Fleming's Right-hand Rule,* as shown in the diagram in Figure 54.

Fleming's right-hand rule is explained as follows:

> With the **thumb, forefinger,** and **middle finger** of the right hand all held at right angles to one another, let the **thumb** point in the direction of the motion, the **forefinger** in the direction of the lines of force, and the **middle finger** will point in the direction of induced e.m.f.

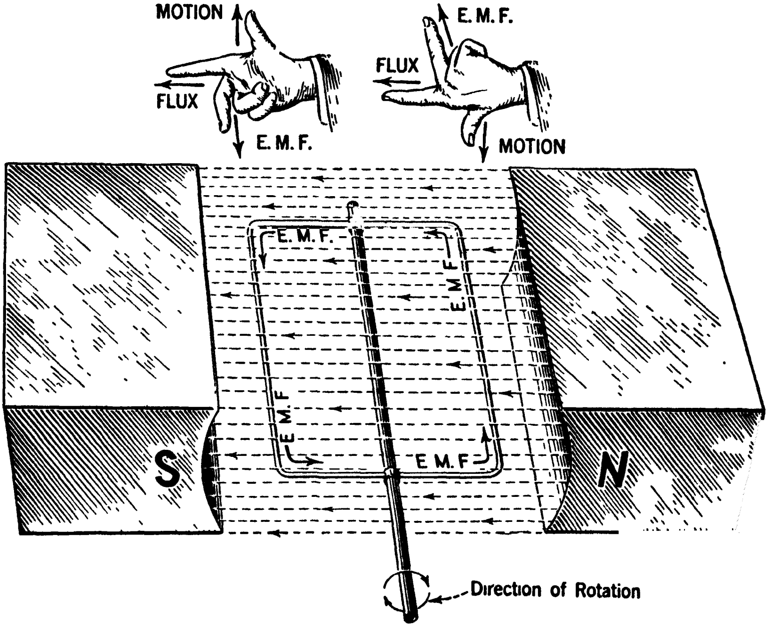


FIG. 55—Another application of Fleming's Right-hand Rule to determine the direction of the induced e.m.f. set up in a rectangular loop of wire when rotating on its axis in a clockwise direction through a magnetic field.

Carefully examine the hands in the drawing in Figure 55 which clearly show the application of Fleming's rule to the effects set up in a rectangular loop of wire when it is being rotated on its axis in a clockwise (or right-hand direction) through a magnetic field. Current will circulate entirely through the loop when it cuts through the lines because the loop forms a closed metallic circuit. It will be noticed, however, that for the set of conditions we have shown in the drawing (that is, with the N pole to the right and the S pole to the left, and the right side of the loop moving downward through the field, and the left side of the loop moving upward through the field) the induced pressure and current will be in a direction away from the reader on the right side of the loop and toward the reader on the left side.

The following facts explain, in general, the results to be expected for various changes in the path which a conductor could be made to take through a magnetic field. The pointer of a galvanometer, if connected to the loop, would deflect a certain amount first to one side and then to the opposite side of zero if the loop were rotated or moved in a vertical direction across the lines up and down. If the loop were moved across the lines in such a way that it followed a diagonal path, then lesser amounts of current would be obtained as indicated by small deflections of the pointer, providing, of course, that for all cases the same rate of movement of the loop is maintained. Or, if the loop is moved parallel to the lines and, therefore, does not cut through the lines, no induced current will be obtained nor will any deflection of the pointer be observed.

*When a circuit is "closed" and "opened" the current does not rise from a zero to maximum value instantly, nor does the current fall from maximum to zero instantly; a short interval of time is required for these changes to occur.* The purpose of the several views in Figure 56 is to illustrate pictorially three conditions, namely: (1) How current gradually rises in strength on the "*make*" *or closing of a circuit* by throwing a switch (views *A* and *B*); (2) how the current flows at a steady value an instant or two after a circuit is closed and does not vary in intensity if the circuit remains closed, provided the circuit conditions remain unchanged (view *C*); (3) how the current gradually decreases in strength from its steady value and drops to zero on the "break" *or opening* of a circuit by pulling a switch (views *D* and *E*).

Since every change in current strength will produce a corresponding change in the number of lines of force produced by the current then we can assume that while current flows through a wire, and progressively increases in value, the lines of force build up and expand outward into space for some distance. When the current flow becomes steady or constant the lines remain stationary, i.e., they do not vary in number or density. A "constant current" is an unvarying current. When current in a wire progressively decreases, the lines gradually diminish in number, contract back on the wire and, finally, when the current ceases to flow, the lines disappear entirely.

Thus, from Figure 56, we learn that on the "make" and "break" of a direct-current circuit the rise and fall in the intensity of the current causes a corresponding change in the magnitude of the magnetic field and, also, that the *changes* in current strength and variations in flux strength are only *momentary*.

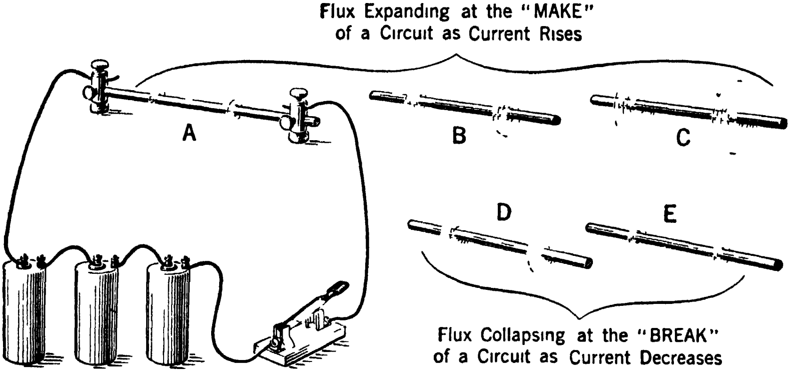

Flux Expanding at the "MAKE" of a Circuit as Current Rises
A
B
C
D
E
Flux Collapsing at the "BREAK" of a Circuit as Current Decreases

FIG. 56. Illustrating the rise and fall of lines of force due to a change in the intensity of current on the "make" and "break" of a circuit.

**How an E.M.F. is Induced in a Secondary Circuit by Variations of the Magnetic Flux Set Up by a Changing Current in the Primary.**—The principles already explained relating to the setting up of a current in a conductor by causing a flux to cut across it will again be used, but this time the results will be obtained without moving either one of the wires. The circuit arrangement is shown in Figures 57 and 58.

Figure 57 shows the action during the "make" and the primary. At this instant the current begins to rise and the lines of force it produces also increase in numbers, and in another instant they will have reached out sufficiently far to cut through the secondary conductor. This effect of the primary on the secondary induces an e m f in the secondary in the direction designated by the arrows, and the lines set up by the momentary flow of current are shown as small magnetic whirls along the secondary

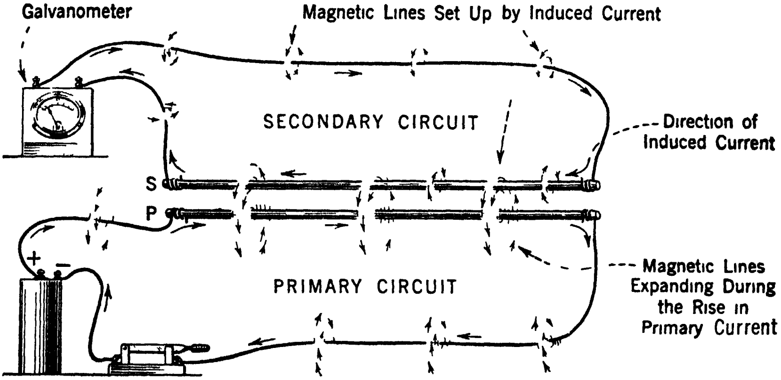

Galvanometer
Magnetic Lines Set Up by Induced Current
SECONDARY CIRCUIT
Direction of Induced Current
S
P
+
−
PRIMARY CIRCUIT
Magnetic Lines Expanding During the Rise in Primary Current

FIG 57—Showing why an e m f is induced in the secondary circuit during the "make" of the primary circuit, that is, when the primary circuit is closed

Figure 58 shows the action during the "break" of the primary At this instant the primary current begins to fall, and the lines, as they contract and fall back on the primary, cut through the secondary conductor in a direction *opposite* to their movement during the "make" of the primary. The cutting action of the lines

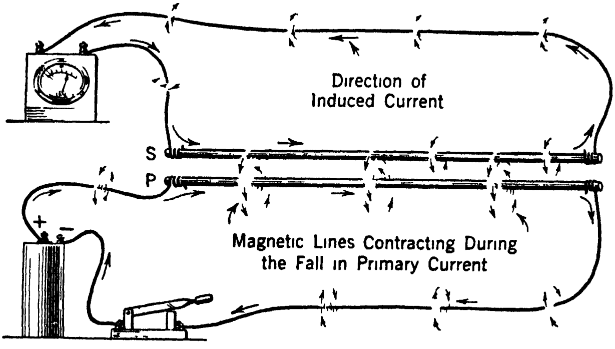

Direction of Induced Current
S
P
+
−
Magnetic Lines Contracting During the Fall in Primary Current

FIG 58—Depicting the electrical action while an e m f is being induced in the secondary circuit during the "break" of the primary circuit, that is, when the primary circuit is opened

this time induces an e.m.f. in the secondary in the opposite direction to the previous induction. This change in direction is denoted by arrows. Observe that the secondary e.m.f. and primary e.m.f. are now in the same direction, and also that the magnetic whirls assume similar directions.

The above two actions illustrate the fact that the secondary *opposes the induction* of current in it by the direction that its lines take when compared to the primary's field, and the secondary also *opposes the stopping* of the current induced in it the second time by the change in direction of its magnetic lines. In brief, in one instance the primary and secondary fields are opposed, and in another instance they aid each other.

The effect of magnetic lines expanding and contracting for increases and decreases in current through one circuit is made use of to produce an e.m.f. and current in some other circuit. Both circuits, or their parts, although usually independent, are in close mechanical relationship, i.e., coupled to each other but with no physical connection between them. Stated in a few words, the principle is simply that a changing magnetic flux set up by the conductors of one circuit reaches out and links through, or cuts through, the conductors of a neighboring circuit. Coils are employed to provide this coupling between two such circuits so that the proper magnetic effects will be set up by one circuit and the desired amount of voltage will be available from the other circuit. This principle is illustrated in the drawings in Figures 57 and 58. This is one method for generating an e.m.f. by electromagnetic induction without the necessity of moving wires or moving coils, as we have heretofore been doing in our experiments.

**Law Relating to the Amount of Induced E.M.F.**—Suppose in Figure 54 that the magnetic flux consists of 100,000,000 lines of force. It would be found that if rod *AB* was made to cut these 100,000,000 lines in exactly one second, the pressure set up along the rod (that is, between its opposite ends, or between *A* and *B*) would be *one volt.* This relation between the amount of the induced electromotive force, measured in volts, the strength or density of the flux, and the rate of cutting the lines should be learned.

All the following conditions have a direct bearing on the amount of the pressure induced in a conductor when cutting, or being cut by, lines of force:

(*A*) The strength or density (number of lines per unit area) of magnetic flux at the point where the conductor is acting at any instant.

(*B*) The number of turns in the coil or length of the conductor actually being acted upon by the lines.

(*C*) The angle which the conductor makes with the direction of the lines, as determined by the path through which the conductor moves as it cuts across the lines.

(*D*) Rate of motion, or the number of lines cut per second.

**The Strength of the Induced E.M.F. Depends Somewhat on the Shape of the Magnetic Circuit and Its Material.**—Each of the three electromagnets at the right in Figure 59 has a more efficient form of magnetic circuit than the electromagnetic at the left because the length of the air gap through which the lines must pass is shorter in one case than in the other. A short air gap strengthens the magnetic field for a given set of conditions, and thus for certain movements of a loop of wire through the flux more lines of force will be enclosed or cut by the loop. In some types only one electromagnetic winding is mounted on the iron core, whereas in the other types more than one winding is used, this being done to increase the ampere-turns. The distance between the poles which governs the size of the air gap is carefully considered in practical

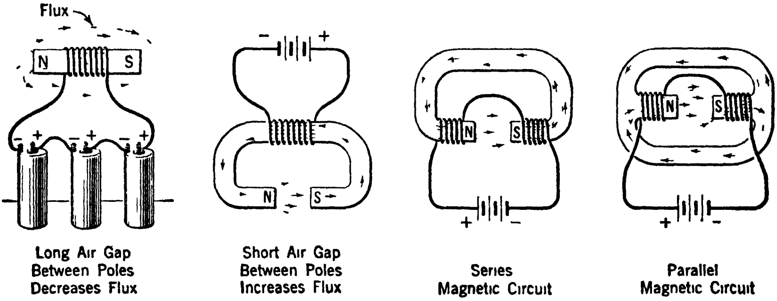


FIG. 59.—Illustrating the magnetic circuits and the flux produced by electromagnets of different forms and types

machinery to keep the reluctance of the magnetic circuit minimum. When coils are connected in series so that current flowing through one must also pass through the other, their turns are so wound as to make the adjacent ends of the windings north and south poles, respectively.

**Lenz's Law.**—This law in concise form states that the direction of the induced e.m.f. is always such as to oppose the motion producing it. Another way of stating this law (which is perhaps easier to understand in view of the fact that we are now familiar with effects produced by magnetic lines of force) is that an e.m.f. is always produced in a direction such that the magnetic lines it sets up oppose any change in the existing magnetic lines.

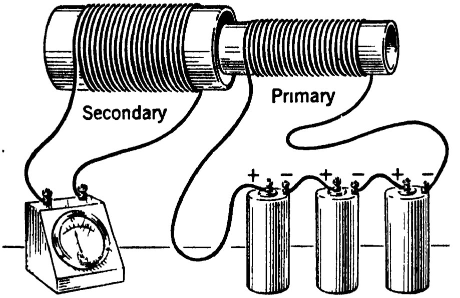


FIG. 60.—An experimental transformer of simple design and construction may be used to illustrate principles of electromagnetic induction

Refer to Figure 60 showing two coils, one a primary and the other a secondary; together they constitute a transformer. A practical explanation of Lenz's law may be given by moving these coils with respect to each other. Let us assume that the current in the primary coil is such that it makes the polarity at the left-hand end *north.* When the primary is moved into the secondary the flow of induced current in the latter coil makes its polarity at the right-hand end also north. Thus, respective poles of both coils have opposite polarity and, therefore, the effect set up between them is one of *repulsion.* However, when the primary is withdrawn from the secondary the induced current in the latter is reversed and reverse polarity will be set up at the right-hand end of the coil. We now have a condition where the left-hand end of the primary is north (note that the polarity of the primary does not change because it is supplied with a steady source of e.m.f. by the dry cells) and the right-hand end of the secondary is of south polarity. A magnetic attraction now exists between the coils that tends to oppose their separation. It is only while the coils are moved with respect to each other and the induced current flows and reversed magnetism is set up about the secondary that we have these effects of attraction and repulsion. It is seen in every case that the magnetic attraction and repulsion tend to oppose the motion of the primary coil.

**Self-Induction.**—This is the name given to that property of an electric circuit which tends to oppose any change (increase or decrease) in the strength of the current in the circuit. The effects of self-induction are present only at such times as a current is changing in intensity. The magnetic lines which always accompany a current begin in a wire at the very center of its core. Thus, when current rises the lines build up *outward* and pass through the very wire which is producing them. On the contrary, when current falls the lines recede *inward* on the wire and cut the wire in the opposite direction to the first instance cited. This cutting action on a conductor by its own lines induces an e.m.f. in the conductor first in one direction for an increase in current and, secondly, in the opposite direction for a decrease in current. Thus, we see that the induced e.m.f. at one time tends to oppose the establishment of a current in a conductor and at another time it tends to prevent the current from dying out. *The induced e.m.f. is known as the induced e.m.f. of self-induction.* The student must understand that the e.m.f. of self-inductance is another e.m.f. acting on a circuit and separate from the usual e.m.f. which is applied to any conductor in order to make current flow in the first place.

**Mutual Induction.**—An induced e.m.f. is set up in a secondary by changes in primary current, and the secondary field resulting acts on the primary field similarly to a primary acting on a secondary. Thus, when two independent circuits are so associated that magnetic effects set up by one circuit induce e.m.f.'s and currents in the other circuit, and the latter also sets up magnetic effects of its own, the two circuits are said to react on each other. This is known as *mutual induction,* and the circuits are said to possess the property of *mutual inductance.* Figures 57 and 58 both show two independent fields reacting on each other. One magnetic field is due to the *inducing current* flowing in the primary (*P*) and the other is due to the *induced current* in the secondary (*S*).

**Inductance.**—This term relates to the energy stored up in the magnetic flux associated with a coil or circuit through which an electric current flows. Inductance is a measure of the amount of this magnetic flux. The property known as "inductance" possessed by a circuit tends to prevent any change in the value of current flowing through the circuit. This may also be called the "self-inductance" of the circuit.

The amount of inductance, measured in the unit "henry," is determined by the amount of voltage that will be induced in a coil or circuit by the current changing at a given rate. Thus: "*A circuit is said to have an inductance of 1 henry when a current changing at the rate of 1 ampere per second will induce therein an e.m.f. of 1 volt.*"

**Non-inductive Circuit—How Effects of Self-inductance within a Circuit May be Neutralized.**—The fields set up along the turns of a coil can be made to neutralize one another if the turns of the coil are wound so that the field around each turn opposes in direction the field around an adjoining turn. The current in each turn must be equal, and adjacent turns should be close together. A coil wound to produce this result is shown in Figure 61. The coil is said to be non-inductive because practically no field is established around the coil when current flows. Coils of this general type are employed for resistor units in instruments such as Wheatstone bridges, meters, and in any circuits where resistance is required but inductive effects are undesired.

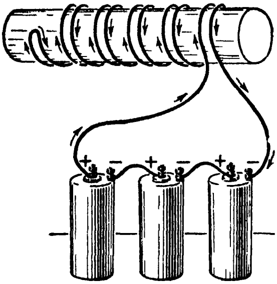


FIG. 61.—If a coil is wound in the manner shown the magnetic fields set up along its turns neutralize one another.

**Sucking Action of a Solenoid.**—Since all magnetic fields possess similar properties a solenoid will attract iron when current flows through it in the same way a bar magnet will attract iron as shown in Figure 62. The flux seeks the path through the iron plunger in preference to passing entirely through air, and this magnetizes the plunger, causing it to be attracted by the coil. The plunger is drawn into or sucked into the coil, and does not stop moving until it centers itself in a position where it will accommodate the greatest amount of flux. It remains unmoved in the coil so long as the current flows at the proper value to provide the requisite amount of flux to hold the plunger from being pulled back by the spring. This principle is utilized commercially in the operation of protective devices called "circuit breakers." These devices automatically trip, open a circuit, and shut off the power when the current becomes excessive for any reason. A spring is adjusted to the proper tension so that the plunger is sucked into the coil only under extreme conditions. This idea can be used for relay operation, or any form of tripping device.

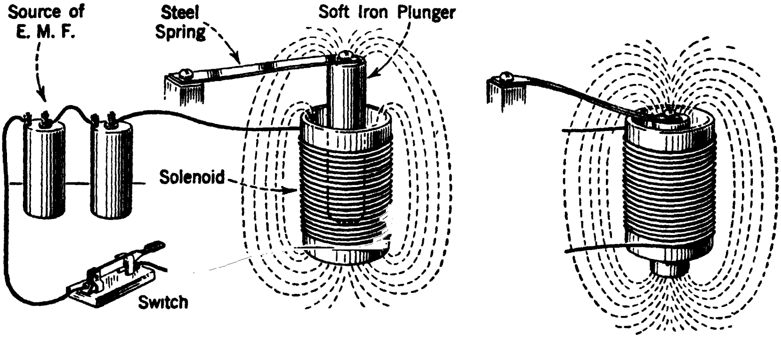


FIG. 62.—The sucking action of a solenoid is easily understood from this pictorial illustration.

## PROBLEMS ON CHAPTER IV

**1.** What does Lenz's law state?

**2.** If an air-core coil is carrying a current, and a bar of soft iron is inserted into the coil, what effect will be produced?

**3.** Explain the principle of the sucking action of a solenoid.

**4.** What phenomenon always exists when current flows?

**5.** Either one of two conditions must be satisfied before an e.m.f. can be induced in a wire or circuit. What are these conditions?

**6.** State the right-hand thumb rule for determining the polarity of a solenoid and draw a simple sketch illustrating same.

**7.** (*a*) What happens when an "open" conductor moves across a magnetic field?
(*b*) What happens when a "closed" conductor moves across a magnetic field?

**8.** State the right-hand thumb rule for determining the direction of the magnetic flux around a current-carrying wire.

**9.** Explain briefly what is meant by the following terms: (*a*) self-inductance, (*b*) mutual inductance.

**10.** What is Fleming's right-hand rule?

**11.** What is the meaning of the term "ampere-turns"?

**12.** How many ampere-turns are there in a coil consisting of 300 turns and through which a current of 0.5 amp. is flowing?

**13.** (*a*) What is an electromagnet?
(*b*) What is magnetomotive force?

**14.** How may the effects of self-inductance be neutralized?

**15.** In general, what governs the amount of the e.m.f. induced in a conductor when it is cutting, or is being cut by lines of force?

**16.** When current flows through a coil why are there north and south poles set up at the respective ends of the coil?

**17.** Do the magnetic lines produced by a horseshoe magnet have characteristics different from the lines produced by an electromagnet? Explain.

**18.** Suppose a current of a certain value flows through a coil having an air core. How could you increase the amount of flux set up by this coil without altering the winding itself in any way? State all the methods you know of for accomplishing this.

**19.** Is there any difference between a solenoid and a helix? Explain.

**20.** In what manner would you move a conductor through a magnetic field so that no e.m.f. would be induced in the conductor? Suppose this were an experiment what instrument would you connect to the ends of the conductor to prove that you were correct in your statement?

# CHAPTER V

# RESISTANCE AND CONDUCTION

IN GENERAL, MATERIALS ARE CLASSIFIED EITHER AS CONDUCTORS, INSULATORS OR PARTIAL CONDUCTORS, ACCORDING TO THEIR RELATIVE CONDUCTIVITY TO THE FLOW OF ELECTRIC CURRENT. A PRACTICAL UNDERSTANDING OF RESISTANCE MEASUREMENTS CAN BE OBTAINED FROM THE SOLVED PROBLEMS IN THIS CHAPTER

THERE are three very important quantities that govern the operation of every electrical circuit. These quantities are *current*, *electromotive force*, and *resistance*. To have a thorough understanding of the relation between the amount of current flowing in a circuit, or part of a circuit, to the amount of electrical pressure that forces the current to flow is quite impossible unless one also has a good working knowledge of the quantity "Resistance."

Hence, in this chapter we will deal chiefly with *resistance* and *conduction*, the latter being the inverse of resistance. The subjects pertain to explanations about different materials and their characteristics with regard to the ease or difficulty with which current will flow through them; also, how a change in temperature will change the resistance of a material; and the calculation of the resistance of wire, and so on. The next chapter will explain in detail about the electrical circuit itself and how the three quantities mentioned above, namely, current, electromotive force, and resistance, are always associated together in a definite relationship which was discovered by George Simon Ohm, who gave to electrical science the famous and invaluable Ohm's Law.

It will be seen that resistance has to do with different kinds of materials that are used in the construction of an electrical circuit and the opposition that such materials offer to the progressive movement of its electrons, from atom to atom through the material, whenever pressure is suitably applied. It is to be remembered that the electron in motion is the electric current and that the value of the current is measured in the unit "*ampere.*" Also, the pressure or electromotive force that is responsible for causing the electron movement is measured in the unit "*volt,*" and the resistance of the material which hinders the free movement of the electrons is measured in the unit "*ohm.*" These units have been defined in Chapter I.

The word "*resistance*" should be familiar to everyone since it is frequently encountered in our everyday life, and wherever the word is used it generally has one meaning which expresses an "*opposition*" of some sort. Many examples could be given showing how this applies, but the following ones are sufficient. If you undertake to do any kind of work, regardless of whether the task requires mental or physical effort, there are oppositions in one form or another that must be met and overcome before the work can be accomplished. Just what these oppositions are will depend, of course, upon the nature of the work. When you walk or run there are oppositions or resistances constantly present that retard your action. No doubt you have had the experience of rowing a boat through rough water, or against the tide, and found that a much greater effort was required to make the boat move forward than if the water were smooth and calm. Even in the latter case, that is, with the water smooth, the pull on the oars (which represents the energy expended in overcoming the opposition of the water which otherwise would prevent the forward movement of the boat) is often sufficient to tire out, in a short time, anyone but a strong person.

A good analogy is always at hand in the case of hydraulics, or water running through a pipe under a certain head pressure, to illustrate the relation existing between *pressure, rate of flow,* and *opposition* or *resistance.* It is easy to understand that water will flow fast or slow according to the pressure, but the oppositions in any particular system also have an important bearing on the rate of the flow, as we will explain. Water running through a pipe, even under a strong head pressure, is retarded to some extent because as it rushes along it is constantly in contact with the inner walls of the pipe and this creates a certain amount of friction. If the pipe has a fairly large diameter, and its inner surfaces are clean and smooth, the water will then flow with comparative ease, but if rust and silt are allowed to collect in the same pipe, either along its length, or at bends, elbows or joints, it will require more pressure to force the same quantity of water through than in the first case, or when the pipe was clean.

Thus we see that rust and silt form an *obstruction* or *resistance* to the movement of water and this must be added to other oppositions in the pipe line. In general, the various oppositions in a water-supply system would include the inner wall resistance as determined by the total length of the pipe and its inner surface condition, that is, whether smooth or rough, the pitch of the pipe at different locations, the area of cross-section, and the size of the pipe at the end where the water flows out, the latter usually being regulated by a valve.

Now suppose that instead of thinking of the opposition or resistance presented to the flow of water by any piping system we thought of this system only in terms of the *ease* with which water was *conducted* through it. We could then compare two different systems and say that one conducted water more readily than the other. Here we have the use of the word "conducted," and it is evident that we have simply another way of looking at the same conditions. So, whether we say conduction in one system is better than another, or whether we say that the latter system has a higher resistance to water flow than the former, we would in either case have conveyed the same idea. This illustrates the practical use of the terms "resistance" and "conduction."

**Electrical Resistance.**—Similar conditions of *resistance* and *conduction* are met with in the case of an electric current flowing through a circuit. First will be discussed the subject of resistance and, following that, the subject of conduction.

Although the amount of current passing through a circuit depends primarily upon the amount of pressure that causes it to flow, yet the fact remains that the *current strength is limited by the resistance of the circuit.* Resistance is a property possessed by all substances that opposes the free movement of electricity through them. All materials have this property, but in some it is more pronounced than in others, and as a result substances are classified under two heads, namely: *conductors* and *non-conductors or insulators.*

After all, the resistivity of substances is only comparative and, therefore, it can be said that conductors are those materials which offer relatively low resistance to current flow and insulators are those which offer a very high resistance as compared to conductors. For all practical purposes an insulator is supposed to completely block the flow of current, and high-grade insulators come very near doing this even when subjected to excessively high voltages.

Just how much a certain material will oppose current flow depends in general upon its natural properties, its physical dimensions, or size, and its temperature.

**Definition of a Standard Ohm.**—The unit in which resistance is measured is the **ohm,** as heretofore stated, and is represent by the letter ($R$) in equations and also by the symbol ($\Omega$) which is the Greek letter omega. The *standard value of an ohm* is defined as that resistance offered to an unvarying electric current by a column of pure mercury 106.3 centimeters long, of uniform cross-sectional area, and weighing 14.4521 grams at a temperature of melting ice, or 0° C., which is the same as 32° F.

Although the following does not strictly define an ohm, and only expresses the relationship of an ohm to voltage and current, yet it is often called a definition. "An ohm is said to be that resistance possessed by a circuit which allows but one ampere of current to pass when an electromotive force of one volt is applied to the circuit."

**Resistance in a D-C Circuit.**—In a direct-current (d-c) circuit resistance can be calculated very easily, inasmuch as the only opposition presented to the current is by the materials which comprise the circuit, and since all circuits are made up mainly of wire of some kind or other then the opposition is due principally to the wire. It is only at the closing or opening of a d-c circuit that oppositions other than the resistance of the wires are introduc which affect the flow of current. When the current reaches i steady value and flows without interruption in a d-c circuit, th only the resistance of the materials limits the current.

**Resistance in an A-C Circuit.**—Current flow in an alternating-current (a-c) circuit is affected similarly by the materials an wires as in a d-c circuit, and also by another form of resistance due to the inductance of the circuit. This is explained as follows: In an a-c circuit the current is constantly changing in intensity, and this current produces magnetic lines of force which likewise change in magnitude. Hence, in an a-c circuit an electromotive force is induced in the wires and coils which make up the circuit, this being accounted for by the action of the changing lines of force cutting the very wires in and around which they exist. In every case the induced e.m.f. *opposes* any change in current strength. The induced e.m.f. may reach comparatively high values and seriously retard the current if coils are used having too many turns of wire which would set up an excessively strong varying magnetic field around the coil for the particular circuit in question. Thus, we say that an a-c circuit contains inductance due to the wires used in the construction of apparatus and the wires used to supply power and connect the parts. We think of inductance particularly in the use of a coil because of the greater concentration of the lines of force in a given space when the conductors are wound in the form of a coil.

The e.m.f. induced in an a-c circuit (because of changing current and consequent action of the magnetic lines on the conductors, which tends at all times to oppose the changes in current, as just explained) is a form of resistance called *inductive reactance*, which is measured in the same unit "ohm" as is the usual resistance presented by the wires or materials.

Now if an a-c circuit contains capacitance, such as could be easily provided by inserting a condenser in a circuit, there still will be another form of resistance present, because the alternating current will charge this condenser. Suppose the condenser used mica between its metal conducting plates. The mica will take on an electric charge, but in so doing the current does not actually pass through this material, as it would pass through copper wire for example. This is because the atoms of the mica (the mica is an insulating material) do not possess the necessary free electrons that can be forced to move progressively from atom to atom in the material, but rather the electrons in the mica atoms are merely pushed to one side, or shifted slightly from their usual positions in the atoms by the e.m.f. in the circuit. It requires an expenditure of force, or a certain amount of e.m.f., to cause this displacement of electrons in the atoms of the mica, and when in this stressed condition the condenser is said to be charged. This form of resistance is called *capacitive reactance,* and it is also measured in the unit "ohm."

The student should know from the start that current does not flow through insulating materials because such materials are lacking in free electrons which are the conductors of electricity, but an insulating material used in a condenser gives the effect of current passing through it since it can be charged and discharged, the action of its electrons being displaced in one case, and returning to their normal or unstressed positions in the other case.

Thus, if an a-c circuit contains coils and condensers, or as we would ordinarily say, contains inductance and capacitance, there will be three different forms of resistance present and acting at the same time. To sum up our statements, the three resistances are as follows:

(1) Resistance presented by the materials.
(2) Resistance due to inductive reactance.
(3) Resistance due to capacitive reactance.

Combining these resistances and knowing that they all affect the flow of current we have a term which expresses the sum total of the oppositions; this term is *impedance.*

From these preliminary facts it is apparent that resistance is a factor which must be considered in all a-c and d-c circuits. In a d-c circuit resistance is found in only one form, but in an a-c circuit it is present in more than one form as just outlined. The reason for again referring to this is that we often want to distinguish between resistance that materials of the circuit offer and other resistances due to the presence of inductance, or capacitance, or both. The resistance due to the natural physical properties of materials or wires used is referred to as *ohmic resistance.*

It should now be clear that no electrical circuit could be designed without having some resistance. In some cases an excessive amount of resistance is undesirable, and in other cases resistance is inserted purposely to limit the flow of current. Keep in mind that all substances have this property and that metals in general have by far less resistance than other substances. Therefore, it is obvious why metals serve best as carrying agents of electricity.

**Electrical Conductance.**—Conductance is just the inverse of resistance, as we explained before, and its unit of measurement is the **mho,** which is **ohm** spelled backwards. It expresses the ease with which current will flow in a conducting medium, that is, it indicates the ease with which electrons can be made to move in a progressive order between the atoms of a material when an electrical pressure is supplied.

EXAMPLES.—If a certain conductor, or circuit, has a resistance of ($R$) ohms, its conductance will equal unity (1) divided by ($R$), that is, $1 \div R$. For example, if the resistance of three resistors were respectively 10 ohms, 400 ohms, and 5 ohms, the conductance for each would equal $\frac{1}{10}$ mho, $\frac{1}{400}$ mho, and $\frac{1}{5}$ mho.

The unit "mho" is not used to any great extent in most everyday work, and when used it is generally in the calculation of the resistance of a divided circuit. To find the resistance of a divided or parallel circuit in terms of conductance the following rule should be used. Add the conductances of the several branches in order to first obtain the total conductance of the combination, and this result when *inverted* will give the total resistance of the combination.

The foregoing means that if the conductance of a combination were found to be $\frac{1}{15}$, we invert this fraction and get $\frac{15}{1}$; $15 \div 1$ equals 15, and so we see that the combination would have a resistance of 15 ohms; or, if we had $\frac{3}{16}$ mho as the conductance, this fraction inverted would be $\frac{16}{3}$, and working this out, we would get 5.3 ohms as the answer. Additional explanations will be given about parallel circuits in the following chapter on Ohm's Law.

**The Use of the Terms "Resistance" and "Resistor."**—Resistance is a property of all materials which opposes the free flow of an electric current, as we already know, but considering only the word itself, or "resistance," it is common knowledge that it is used loosely to indicate or identify any device made especially to be inserted in a circuit to limit the current flow. The proper term to apply to a piece of equipment intended for this purpose is "resistor." The term "resistance," in its more correct use, is the inherent opposition offered by all substances to the flow of electrical current.

Three names in general use which designate different types of resistor units are *Rheostat*, *Resistor*, and *Potentiometer*. You will become very familiar with these terms as you advance in your study. Resistance devices are made up in innumerable sizes and shapes to meet any practical condition.

**Rheostat.**—When a resistance unit is constructed to permit the amount of resistance it contains to be altered it is called a "rheostat." Two terminal connections are provided for such a unit; one of the connections goes to the movable contact arm which is firmly pressed against the wire by a spring, and the other to one end of the wire. Simply moving the arm across the wire makes contact on different portions and, hence, more or less of the resistance wire will be included in the circuit in which the device is connected. This action is expressed by saying that resistance is *cut in* or *cut out* of the circuit, as the case may be. Thus, by the use of a rheostat, current in a circuit can be controlled.

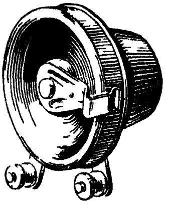


Fig. 63.—One type of rheostat which provides a continuously variable resistance.

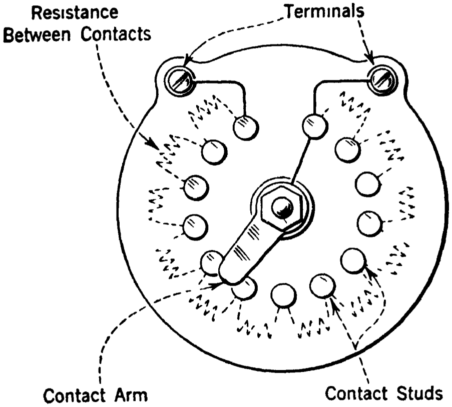


Fig. 64 Another type of rheostat, the resistance of which is varied in "sections" or "steps"

One form of rheostat is shown in Figure 63. Figure 64 is an explanatory drawing of a commercial rheostat for regulating current in the field coils of a motor or generator. It is made with tap connections taken from different portions of the wire, and these taps terminate as brass studs or segments. In this type, when the contact arm or handle is moved over the studs, from one end to the other, sections of the wire are successively cut in or out, and the change in resistance causes the current supplied to the fields to be increased or decreased as the case may be. The resistance of the rheostat in Figure 64 is *varied in sections*, or, as we usually say, *in steps*, but the resistance of the rheostat in Figure 63 is *continuously variable* since the contact on the arm slides along the wire itself.

**Resistor.**—If there is no need for varying the current during the operation of a circuit, then resistors of the *fixed* type can be used to control the flow of current. The resistance of fixed resistors cannot be altered since no mechanical means are provided for doing so. An exception to this is in the case of fixed resistors wound with special wire which changes its resistance with changes in current strength, and these are used to provide automatic regulation for certain kinds of work. Figures 65 and 66 show fixed resistors.

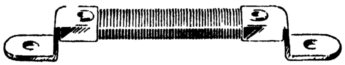


FIG. 65.—Resistance of the "fixed" type, known as a resistor.

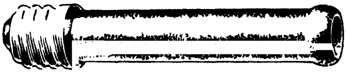


FIG. 66.—A resistor supplied with an Edison base.

**Potentiometer — Voltage Divider.** — The resistor (voltage divider) in Figure 67 consists of many feet of resistance wire wound on a rod of insulating material with tapped connections taken from the wire at certain intervals. A unit of this kind is called a "potentiometer," and its function in a circuit is different from that of either a rheostat or fixed resistor. Although a potentiometer is physically a resistance device it is not used to limit current flow in a circuit, but is used as a convenient method to supply voltages of different amounts to one or more circuits that may be suitably connected to the various terminals. Suppose for the sake of explanation that a battery having an e.m.f. of 30 volts is connected to the extreme ends of this potentiometer, then certain intermediate values of e.m.f. between 0 and 30 volts can be obtained at the taps. Many devices of this type in general use are so constructed that the voltage at the taps can be regulated by using one or more variable resistor elements in the unit. Since a potentiometer is primarily a voltage dividing device it is not usually referred to as a resistor. Potentiometers are built with resistances ranging all the way from a hundred ohms or less to several hundred thousand ohms.

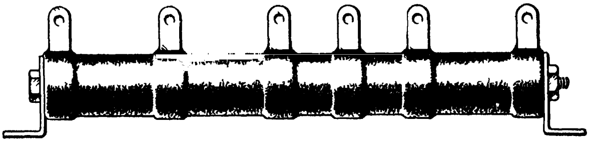


FIG. 67—A resistor of this kind with tapped connections is used as a voltage divider and functions according to the principles of a potentiometer.

**Materials Used for Resistance Purposes—Alloys.** All electrical pieces of equipment built to give a predetermined amount of resistance are constructed, for practical and economical reasons, with the least amount of material and made into a unit of suitable physical proportions as governed by the use to which the part will be put.

To grasp the importance of the idea of size in devices of this kind, just consider for a moment how much copper wire would be required to give a resistance of some comparatively low value, let us say 100 ohms. This can best be explained if we suppose that the resistor shown in Figure 65 has a resistance of 100 ohms. To construct a resistor of equivalent value, or 100 ohms, would take about 10,000 feet of copper wire, provided we used a No. 20 B. & S. gauge wire, and the copper would weigh approximately 30 lbs. No. 20 wire has a diameter of 31.961 mils or 0.03196 inch. These figures are based on the data given in the Wire Table on page 121 of this chapter. It is easy to see that copper wire, because of its low resistivity, is not suited for use as a resistance material, and furthermore, the high cost of such a large bulk of copper would make its use prohibitive for this purpose. Copper is, however, the most widely used material for electrical conductors because of its low restivity. Iron wire and aluminum wire are extensively used for conductors, the iron having a resistivity of about seven times that of copper and the aluminum about 1.6 times. Galvanized iron wire is used on many telegraph lines.

Since pure metals such as copper, iron, aluminum, and so on, have comparatively low resistivity it is necessary to use materials which are alloys to obtain high resistances with reasonably small amounts of material. Alloys are combinations of different materials and are manufactured expressly to give high resistances. The resistance of an alloy can be made much higher than the resistance of the pure metals alone, that is, when not in the combination. Of course, the resistance of any alloy will depend upon the nature of the metals and the percentage of each used. Moreover, alloys are prepared with great care to obtain non-corrodible materials that will remain practically without change in resistance at different temperatures. Materials in this class should remain as nearly constant as possible under normal working conditions. There are some alloys used for the specific purpose of automatically limiting the current in a circuit; the resistance of such materials changes considerably for changes in temperature.

The resistivity of an alloy is greater than pure metals like copper, iron, aluminum, nickel, zinc, chromium, and so on. This is explained by the following example: An alloy, such as manganin, consists of three metals, namely: copper, nickel, and iron-manganese, and when combined in certain proportions the alloy can be made to have a resistance of three or four hundred ohms for each foot of wire when the wire is drawn to a diameter of 0.001 inch. Alloys of some of the materials mentioned above are made to give a resistance of more than 600 ohms per foot when in the form of a wire 0.001 inch in diameter. Notice that a foot of wire, 0.001 inch in diameter, is used as a unit for comparison of materials. This is known as a "mil-foot." Monel metal is an alloy of approximately 71 per cent nickel, 27 per cent copper, and 2 per cent iron. Constantan, another alloy used in rheostats and measuring instruments, consists approximately of 60 per cent copper and 40 per cent nickel. In commercial practice we find rheostats and resistors constructed of rods, or disks, or strips of the resistance *material, or resistance wire wound in coils, and so on. One type consists simply of a metallized deposit on a form of insulating material.*

The wires wound on the parts shown in Figures 63, 64, 65, 66, and 67 are alloys of different kinds. A resistor of one type may use iron wire and another may use carbon ground up and placed in tubes shaped in different forms, and so on. Since some heat is developed by these units the resistance wires on the parts in Figures 63 and 65 are wound on forms of a non-inflammable fibre material and the wires in Figures 64, 66 and 67 are held in place by the use of porcelain.

Engineers who design electrical equipment for heating and other purposes take a great deal of care in selecting the proper material so that it will have the desired resistance and, not only that, the material must have sufficient cross-sectional area to be capable of radiating from its surface whatever heat is generated in the material by the current, at a rate that will never permit the temperature to rise high enough to damage the wire or insulation, if this is used. The *dissipation of heat* is measured in watts since the heat is due to the power supplied, which in turn is represented by the voltage and current in the circuit. You will recall that a watt equals a volt multiplied by an ampere, the watt being the unit of electrical power. Every wire has its safe-carrying current capacity, and if operated within the current limits specified excess temperature conditions will not exist.

**Resistance of Materials Changes with Temperature.**—In any of its forms a resistance material, or any conductor of electricity, dissipates a certain amount of heat proportionate to the current strength and resistance of the material. This relation of current ($I$) and resistance ($R$) is referred to as the "$I^2R$" loss, or heat loss. Changes in temperature of a material alter its resistance, but so long as the temperature remains constant the resistance will remain unchanged.

In general, the resistance of metals increases with a rise in temperature. Carbon is an example of a material that decreases in resistance with an increase in temperature. Other substances that exhibit this same peculiarity are porcelain, glass, and electrolytes. The latter name refers to solutions of water and various salts and acids. A solution of sulphuric acid and water used in lead-acid type storage batteries is called an "electrolyte."

Another curious fact is that a certain substance will have the property of an insulator when cold, but that of a conductor when heated. This property exists to a very small degree in the carbon lamp filament, which has a resistance when cold about twice that which it has when heated to incandescense.

Since in every wire or conductor the electrical energy consumed in setting up a flow of current (that is, in overcoming the resistance of the conducting materials) is turned into heat, then it can be said that some heat is produced in all kinds of electrical apparatus when current is flowing. The heat generated in overcoming *electrical resistance* is comparable to heat generated by *mechanical friction* in the moving parts of machinery.

Certain types of electrical equipment are made expressly for heating purposes, such as electric soldering irons, toasters, percolators, electric heaters, and so on. In all equipment of this kind the heat generated is put to a *useful purpose.* On the other hand, when heat is generated where it is not needed it is wasteful and represents a *loss of energy.* For instance, in an electric lamp which is used only to produce light the heat set up is a loss, and in an electric motor which is used to produce mechanical motion the heat developed by the parts is just so much energy wasted. The function of any resistor or rheostat which is used to regulate the flow of current is to absorb a certain amount of electrical energy applied to a circuit; this energy will be transformed into heat in this part, consequently reducing the amount of energy available to other parts for performing useful work. In any resistance device used for limiting current the energy is wasted in heat instead of performing useful work.

Most of the electrical energy in a circuit may go into heat energy, or less of it may go into heat and more into other forms of energy. In an electric lamp, as just mentioned, heat and light energy are both present. In an active antenna system of a broadcast or commercial transmitter the electrical energy in the conductors is transformed into heat energy and, besides, energy is given off in the form of electromagnetic waves radiated into space. We can neither feel nor see the effects of radio waves in space, but our senses permit us to detect the presence of heat and light energy.

Special care is exercised in manufacturing electrical apparatus to keep the heat produced down to a safe value, and in many installations provisions are made to carry off excessive heat in certain parts by various means, as, for instance, by employing special insulating oil, fan blowers, cooling oils through which water circulates, and so on. These precautions are necessary to prevent an excessive rise in temperature of the parts that might be the possible cause of a breakdown of the equipment.

**Friction—Heat and the Electron.**—In support of the fact that conductors do become warm when current flows and more heat is developed in some substances than in others, we have the electron theory, which tells us that there is friction between electrons and the atoms among which they circulate in traveling through a material. It is thought that heat is produced in a wire or other conductor when current flows, because of the countless numbers of collisions that occur between the electrons and atoms as the electrons are forcibly moved from atom to atom by the e.m.f. or pressure. Thus, an electron encounters friction, and wherever there is friction present a certain amount of heat will be generated. Also, if a comparatively small current passes through a large-sized wire then only a very small amount of heat will be produced, perhaps not sufficient to be noticeable. The same current in a much smaller wire might produce considerable heat. If the electrons had to travel through a long path rather than a short one, the total friction and the total resistance would be increased, hence, more heat would be generated. Keep in mind that there is friction encountered by each electron as it becomes attached to, and detached from, the large number of atoms which make up the conducting materials in circuits. The possible differences in the number and arrangement of the electrons gives us a plausible reason why the friction set up between the moving electrons and atoms is greater in some substances than in others. In this instance we are considering, of course, only the property of a substance and not its size, or cross-sectional area, as in the case of wires of different gauge.

Now consider the heat effect in a certain wire if we double its cross-sectional area. Suppose the same number of electrons move in two wires of unequal size but the length of the path the electrons travel in both wires is the same. For the purpose of explanation assume that the electrons travel not only in the same direction but in parallel rows. Electrons will be packed more closely together in the small wire than in the large one, consequently the total friction resulting in the large wire will be only half as great as in the small one.

**Examples of Loss of Power Due to Heat.**—Suppose a power transformer (which has no moving parts and is used merely to transform an a-c voltage of one value to an a-c voltage of either a higher or lower value) is supplied with 50 kilowatts of electrical power at its input side, and suppose that the transformer delivers from its output side only 48.8 kilowatts of electrical power. For this particular transformer operating under certain conditions the electrical power in kilowatts that is lost in producing heat which is not wanted is 50 − 48.8 or 1.2 kilowatts.

Hence, we can conclude that in all electrical apparatus there is a certain amount of wastage due to heat which is unavoidable, and this must be kept down to a minimum by careful design and proper operation of the equipment.

## CONDUCTORS AND INSULATORS

Considering, from the viewpoint of the electron theory, what happens in a material when it is subjected to an electric pressure will make it fairly easy for almost anyone to understand what causes the difference in electrical action between conductors and insulators. It will also help to impress one further with the convenience of this theory in accounting for the actions that go on unseen in electrical circuits. Once again, let us state that a movement (flow) or so-called drift of electrons from one place to another through any medium, whether it is a metal, a liquid, or air, constitutes an electric current.

According to the electron theory the atoms of one material naturally possess more or less free electrons than the atoms of some other material. Although the free electrons revolve rapidly about the positive nucleus of the atom they are not so firmly bound to it as are another group or inner circle of electrons, which also whirl constantly about the same nucleus and remain associated with it. In each atom there are perhaps but one or two free electrons that can be forced out of their usual positions away from their parent atom by an e.m.f. After being detached from their parent atom these electrons will be moved to some other atom, and in turn one or two electrons will be detached from their atom and they will move to another atom, and so on. This movement or exchange of electrons from atom to atom occurs in the same direction as the pressure or e.m.f. which is forcing them to move.

Since the electron itself is electricity, then the *conduction of current* through any substance *is brought about by the movement of electrons.* Thus, it is easy to figure out that if the atoms of a certain material have a sufficient number of free electrons available, then under a properly applied pressure there will be a flow of current. That is to say, electrons will move progressively from atom to atom through the material from one end to the other, or between the points where the pressure is applied. Hence, any material that is said to pass an electrical current is called a *conductor.* Also, that is why we call any metallic path, or other medium through which an electrical current can be made to flow, *a conductive circuit.*

Now, on the contrary, if the atoms of certain substances have practically no free electrons for the conduction of electricity, then it is reasonable to suppose that such a substance will offer a comparatively high opposition to the flow of current, or in other words, its resistivity will be high. In certain materials there is, for all practical considerations, no conduction, and such materials are called non-conductors or insulators. Materials vary greatly in the amount of requisite electrons for conduction purposes. This is what classifies materials with regard to their resistivity. A chart is given on page 120 of this chapter which shows the properties of materials used for conduction.

From the foregoing statements you can easily reason out that *conductors form one group of substances offering relatively low resistance, whereas insulators form another group that offer high resistance as compared to conductors.*

When speaking in relative terms about the differences between materials and in a case where the resistance of a certain wire is low and its ability, therefore, to conduct electrons is known to be good, then in referring to this wire we would say, "It is a *good conductor.*" Conversely, if the resistance of some other kind of wire is high, its conductance will not be so good and for the latter wire we would say, "It is a *poor conductor.*"

An examination of the chart on page 121 of this chapter giving the resistivity of different materials will show that silver is the best conductor, and copper is almost as good. However, German silver has a much greater specific resistance than that of silver. The resistance of German silver, which is an alloy consisting of a mixture of copper, zinc, and nickel, varies according to the method of manufacture and the materials used. Depending upon the percentage of nickel used in this alloy it can be made to have a resistance of from about 13 to 30 times, or more, the resistance of copper.

To give a reason for this difference in materials, and to review what we have already stated, we will compare silver and copper. It is assumed that when an e.m.f. is applied to silver and copper, the electrons, in the case of silver, are detached with less difficulty from the atoms to which they belong and will move more freely from atom to atom than would those electrons that are detached and moved from atom to atom in the copper. Thus, if an e.m.f. of 1 volt is applied across two faces of a piece of silver having a mass an inch cube, the rate of flow of electrons will be greater from face to face in this metal than if the same voltage were applied to a piece of copper of similar size and tested under like conditions.

Furthermore, let us make it clear that there is no fixed line of demarcation between conductors and insulators; it is simply a question of a material having the required electrons that can be forced to move from atom to atom by a pressure, or that something which we call electromotive force. Calling a material a conductor, a partial conductor, or an insulator is using merely relative terms. Nothing but a perfect insulator would block completely a flow of current. Tests prove that an infinitesimal amount of current, so small as to be measurable only with the most sensitive laboratory meters, passes through even the highest grade insulators known. At the present time there is no substance known that has perfect insulating qualities any more than there is a perfect conductor, or one without resistance.

**Conductors.**—Carbons, all the metals, and solutions of salts and acids are conductors. A few substances are arranged below in the order of their conductivity. Silver heads the list since it is the best conductor.

Silver
Copper
Aluminum
Lead
Zinc
Platinum
Iron
Mercury
Carbon
Acid solutions
Sea-water
Moist earth

**Insulators.**—Some of the well-known insulators are given in the following list.

Dry air
Porcelain
Glass
Shellac
Mica
Slate
Rubber
Paraffin paper
Oils
Dry paper
Wax

Water, dry woods, and the human body are examples of *partial conductors.*

**Insulators Used in Radio.**—All types of insulators are made for the purpose of preventing either short circuits or loss of electrical energy through leakage to the ground. The first requisite of an insulator is that it must block the passage of current at the e.m.f. it will be subjected to under working conditions and, besides, there should be a certain margin of safety for abnormal conditions. We find insulators made in various shapes and forms and of different materials. Just what particular type insulator is selected is determined by the amount of voltage in the circuit in which it will be used and whether it will be installed outdoors or indoors.

An insulator might be located at some point in a circuit where higher voltages are apt to be encountered than would be found in ordinary service. Because of the abnormal conditions possible in any circuit insulators for a particular use should be capable of preventing disruptive high voltages from breaking down the insulating qualities, of course, within certain limitations.

The insulators shown in Figure 68 are two popular types used in the erection of antennas. Insulators of this kind for receiving antennas are comparatively small, being only a couple of inches or more in length and an inch or so in diameter. The small insulators prove adequate because of the feeble signal currents that are carried by receiving antenna conductors. However, when intended for use in transmitting antennas they are made in large sizes of a foot or more in length and several inches in diameter. This is necessary because of the high voltages present in commercial radio transmitting antennas and because of the weight of the heavier wires which they must support.

Observe that the corrugations on the surfaces of the insulators make their lengths along the outside much greater than the actual lengths of the insulators measured from end to end. The increased surface length gives an insulator better insulating qualities, which is particularly advantageous when moisture or dampness collects on its surface. Since water is more or less a conductor of electricity a certain amount of "surface leakage" occurs in damp and stormy weather.

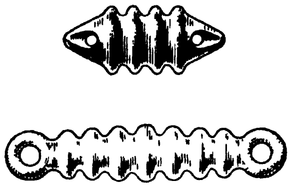


FIG. 68 —Two popular types of insulators used with receiving antennas.

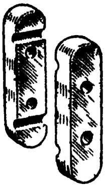


FIG. 69. —Porcelain cleat insulators.

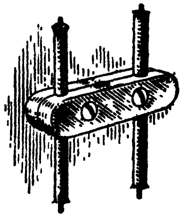


FIG. 70.—Porcelain cleat insulators in place.

Figure 69 shows a pair of porcelain cleats. Figure 70 shows the cleats in place holding two insulated wires, the cleats being screwed or nailed to a ceiling, wall, or support of some kind. Another type of insulator is shown in Figure 71. This is a porcelain tube which allows a wire to be passed through it as illustrated in Figure 72, the tube being installed in a wall or partition.

Figure 73 is a typical receiving antenna installation between an outbuilding and the house where the radio set is located. Notice that insulators of the type if Figure 68 are supporting the long horizontal antenna wire at its opposite ends and an insulator of the type in Figure 71 is used at the window casing where the lead-in wire enters the house.

Insulators of the type in Figures 74 and 75 are employed in commercial radio transmitting equipment. These are made to be installed in decks, bulkheads, or at any place where the lead-in wire from the antenna is carried indoors. These types, in general, are called "deck insulators," and they are manufactured in various sizes to resist puncture or breakdown by e.m.f.'s which reach as

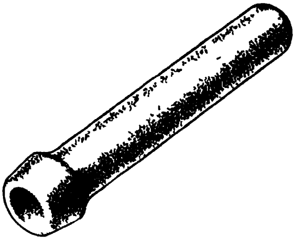


FIG. 71.—A porcelain tube insulator.

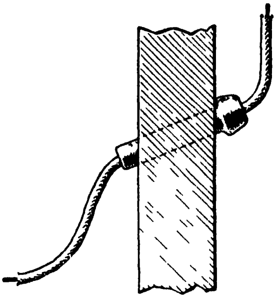


FIG. 72 Showing a porcelain tube insulator in place.

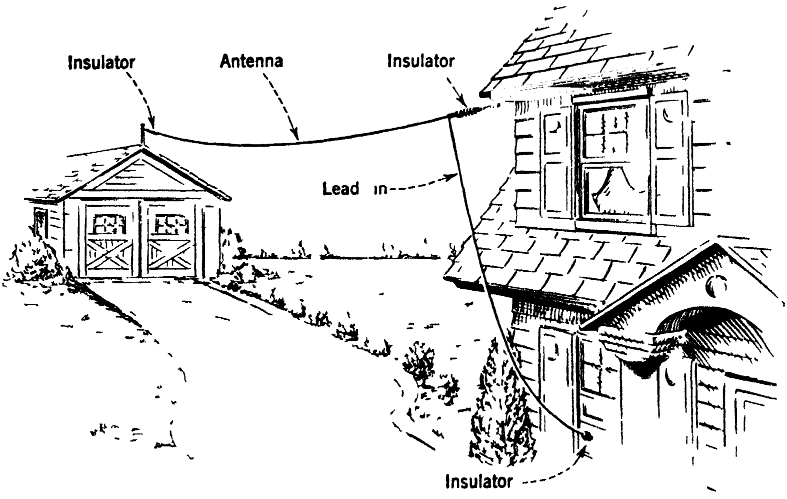


FIG. 73. Illustrating how and where insulators are used in a receiving aerial installation. In an actual installation a lightning arrester (not shown) would be used near the point where the lead-in enters the building.

high as 30,000 volts in some antenna systems. In radio transmitter antennas the working conditions are quite severe because of the high frequencies at which the electric stresses alternate. Also, at times there may be considerable heat developed by the high frequencies and this will have some effect on the insulating qualities of the insulator.

Moisture reduces the dielectric strength of any insulating material. Hence, when materials like porcelain are used they go through a special process of baking in hot furnaces that gives them a smooth glassy surface. If the glazed surface should become cracked or chipped the material will absorb moisture and its effectiveness as an insulator will be materially lowered, and this will result in a reduction of the voltage at which a "flash-over" might occur. This means simply that the insulation will be weakened to the extent that it will allow current to pass through it at voltage lower than that required.

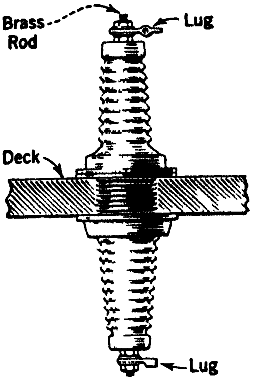


FIG. 74 One type of deck or bulkhead insulator used on ship-board.

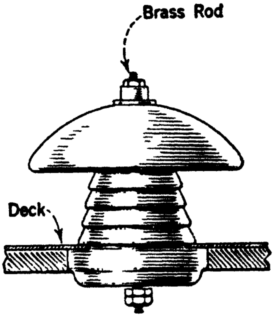


FIG. 75 —Another type of bulkhead insulator.

The insulator in Figure 74 consists of a heavy brass rod moulded into the insulating material with connection terminals at either end. The insulator is threaded as shown, and the upper half carrying this threaded portion is inserted in a hole of proper size cut in the deck or bulkhead. The flange part rests on rubber gaskets, and when the collar is slipped over the lower part and drawn up tightly with a wrench a water-tight joint is provided.

## Properties of Metals

| Metal | Microhm-centimeters at 20° C. | Temperature coefficient at 20° C. | Specific gravity | Tensile strength, lbs./in.$^2$ | Melting point, °C. |
|---|---|---|---|---|---|
| Advance. See Constantan. | | | | | |
| Aluminum | 2.828 | 0.0039 | 2.70 | 30 000 | 659 |
| Antimony | 41.7 | .0036 | 6.6 | ....... | 630 |
| Bismuth | 120 | .004 | 9.8 | ....... | 271 |
| Brass | 7 | .002 | 8.6 | 70 000 | 900 |
| Cadmium | 7.6 | .0038 | 8.6 | ........ | 321 |
| Calido. See Nichrome. | | | | | |
| Climax | 87 | .0007 | 8.1 | 150 000 | 1250 |
| Constantan | 49 | .00001 | 8.9 | 120 000 | 1190 |
| Copper, annealed | 1.7241 | .00393 | 8.89 | 30 000 | 1083 |
| Copper, hand-drawn | 1.771 | .00382 | 8.89 | 60 000 | ...... |
| Eureka. See Constantan. | | | | | |
| Excello | 92 | .00016 | 8.9 | 95 000 | 1500 |
| German silver, 18 per cent | 33 | .0004 | 8.4 | 150 000 | 1100 |
| German silver, 30 per cent. See Constantan. | | | | | |
| Gold | 2.44 | .00342 | 19.3 | 20 000 | 1063 |
| Ia Ia. See Constantan. | | | | | |
| Ideal. See Constantan. | | | | | |
| Iron, 99.98 per cent pure | 10 | .0050 | 7.8 | ....... | 1530 |
| Iron. See Steel. | | | | | |
| Lead | 22 | .0039 | 11.4 | 3 000 | 327 |
| Magnesium | 4.6 | .004 | 1.74 | 33 000 | 651 |
| Manganin | 44 | .00001 | 8.4 | 150 000 | 910 |
| Mercury | 95.783 | .00089 | 13.546 | 0 | −38.9 |
| Molybdenum, drawn | 5.7 | .004 | 9.0 | ....... | 2500 |
| Monel metal | 42 | .0020 | 8.9 | 160 000 | 1300 |
| Nichrome | 100 | .0004 | 8.2 | 150 000 | 1500 |
| Nickel | 7.8 | .006 | 8.9 | 120 000 | 1452 |
| Palladium | 11 | .0033 | 12.2 | 39 000 | 1550 |
| Phosphor bronze | 7.8 | .0018 | 8.9 | 25 000 | 750 |
| Platinum | 10 | .003 | 21.4 | 50 000 | 1755 |
| Silver | 1.59 | .0038 | 10.5 | 42 000 | 960 |
| Steel, E. B. B | 10.4 | .005 | 7.7 | 53 000 | 1510 |
| Steel, B. B | 11.9 | .004 | 7.7 | 58 000 | 1510 |
| Steel, Siemens-Martin | 18 | .003 | 7.7 | 100 000 | 1510 |
| Steel, manganese | 70 | .001 | 7.5 | 230 000 | 1260 |
| Superior. See Climax. | | | | | |
| Tantalum | 15.5 | .0031 | 16.6 | ....... | 2850 |
| Therlo | 47 | .00001 | 8.2 | ....... | ...... |
| Tin | 11.5 | .0042 | 7.3 | 4 000 | 232 |
| Tungsten, drawn | 5.6 | .0045 | 19 | 500 000 | 3000 |
| Zinc | 5.8 | .0037 | 7.1 | 10 000 | 419 |

[*] This table is presented through the courtesy of the U. S. Bureau of Standards.

## Resistance of International Standard Annealed Copper

### American Wire Gauge (B. & S.)

| B. & S. gauge, No. | Diameter in mils, *d* | Area in circular mils, $d^2$ | Ohms per 1000 ft. at 20° C. or 68° F. | Pounds per 1000 ft. |
|---|---|---|---|---|
| 0000 | 460.00 | 211,600 | 0.04901 | 640.5 |
| 000 | 409.64 | 167,810 | 0.06180 | 508.0 |
| 00 | 364.80 | 133,080 | 0.07793 | 402.8 |
| 0 | 324.95 | 105,530 | 0.09827 | 319.5 |
| 1 | 289.30 | 83,694 | 0.1239 | 253.3 |
| 2 | 257.63 | 66,373 | 0.1563 | 200.9 |
| 3 | 229.42 | 52,634 | 0.1970 | 159.3 |
| 4 | 204.31 | 41,742 | 0.2485 | 126.4 |
| 5 | 181.94 | 33,102 | 0.3133 | 100.2 |
| 6 | 162.02 | 26,250 | 0.3951 | 79.46 |
| 7 | 144.28 | 20,816 | 0.4982 | 63.02 |
| 8 | 128.49 | 16,509 | 0.6282 | 49.98 |
| 9 | 114.43 | 13,094 | 0.7921 | 39.63 |
| 10 | 101.89 | 10,381 | 0.9989 | 31.43 |
| 11 | 90.742 | 8,234.0 | 1.260 | 24.93 |
| 12 | 80.808 | 6,529.9 | 1.588 | 19.77 |
| 13 | 71.961 | 5,178.4 | 2.003 | 15.68 |
| 14 | 64.084 | 4,106.8 | 2.525 | 12.43 |
| 15 | 57.068 | 3,256.7 | 3.184 | 9.858 |
| 16 | 50.820 | 2,582.9 | 4.016 | 7.818 |
| 17 | 45.257 | 2,048.2 | 5.064 | 6.200 |
| 18 | 40.303 | 1,624.3 | 6.385 | 4.917 |
| 19 | 35.890 | 1,288.1 | 8.051 | 3.899 |
| 20 | 31.961 | 1,021.5 | 10.15 | 3.092 |
| 21 | 28.462 | 810.10 | 12.80 | 2.452 |
| 22 | 25.347 | 642.40 | 16.14 | 1.945 |
| 23 | 22.571 | 509.45 | 20.36 | 1.542 |
| 24 | 20.100 | 404.01 | 25.67 | 1.223 |
| 25 | 17.900 | 320.40 | 32.37 | 0.9699 |
| 26 | 15.940 | 254.10 | 40.81 | 0.7692 |
| 27 | 14.195 | 201.50 | 51.47 | 0.6100 |
| 28 | 12.641 | 159.79 | 64.90 | 0.4837 |
| 29 | 11.257 | 126.72 | 81.83 | 0.3836 |
| 30 | 10.025 | 100.50 | 103.2 | 0.3042 |
| 31 | 8.928 | 79.70 | 130.1 | 0.2413 |
| 32 | 7.950 | 63.21 | 164.1 | 0.1913 |
| 33 | 7.080 | 50.13 | 206.9 | 0.1517 |
| 34 | 6.305 | 39.75 | 260.9 | 0.1203 |
| 35 | 5.615 | 31.52 | 329.0 | 0.0954 |
| 36 | 5.000 | 25.00 | 414.8 | 0.0757 |
| 37 | 4.453 | 19.83 | 523.1 | 0.0600 |
| 38 | 3.965 | 15.72 | 659.6 | 0.0476 |
| 39 | 3.531 | 12.47 | 831.8 | 0.0377 |
| 40 | 3.145 | 9.89 | 1049 | 0.0299 |

## MEASUREMENT AND CALCULATION OF RESISTANCE

*Since the greater portion of power circuits and radio circuits consist of wire to conduct the electrical current we will devote the balance of this chapter to the subject of wire.*

**Wire Gauge Tables.**—There are several standard wire gauge tables, differing somewhat from one another, in general use for wire calculations. The B. & S. gauge originated by the Brown & Sharpe Manufacturing Co. is the one in most common use in this country and therefore it is often called the American gauge. The B. W. G. table (Birmingham Wire Gauge) is considered the standard in Great Britain. The table for the *B. & S.*, or *American gauge*, will be found on page 121 of this chapter. There it will be seen that a few relations are given, such as diameter, area, weight, etc., for each size wire from No. 0000 (pronounced "four naughts") to No. 40, this being a very fine wire not much larger than a coarse human hair. Notice that the largest wire is given the smallest number, and the numbers increase up to 40 as the wire sizes decrease.

**Microhm.**—In measuring resistances it is often convenient to use as a unit of value the one-millionth part of an ohm, which is called the microhm. If any value of resistance is stated in ohms the same value may be expressed in microhms by multiplying the given value in ohms by 1,000,000. For example: If a certain conductor has a resistance of 0.0058 ohm its equivalent value in microhms is 0.0058 × 1,000,000 or 5800 microhms.

**Megohm.**—When very high resistances are measured the unit called a *megohm* is used. One megohm equals 1,000,000 ohms.

**Temperature Coefficient of Resistance.**—Refer to the table on page 120 of this chapter headed "Properties of Metals." In order to compare different metals in making up a table similar to this one a standard unit is necessary, and for this the Bureau of Standards has adopted the resistivity of annealed copper standard which has a *temperature coefficient* of 0.00393 at 20° C. You will see this value in the second column opposite copper. Although "temperature coefficient of resistance" appears to be a big term yet it is easy to understand, for it merely indicates a *value which tells us how much the resistance of a material will increase for every degree rise in its temperature.* The values of the temperature coefficients are based upon a change in resistance from 20° C. If the original temperature of the metal were something other than 20° C., then, when compiling a table, the temperature coefficient values would not be the same as those given in this table.

**Specific Resistance.**—Let us first mention that the opposition to current flow by a substance is called its "resistivity" and the total opposition offered by an electrical circuit is called its "resistance," or "total resistance."

The resistivity of a unit length of material (as measured by the distance the current must travel in passing between opposite faces of the material) and a unit cross-sectional area at the predetermined temperature is known as its "specific resistance." The table shows that the resistivity values vary for different metals. Either a unit centimeter, or a unit inch, may be used as the basis for this measurement. If we have a block of copper 1 inch on all sides it is said to be an "inch cube" in dimensions, and if it is 1 centimeter on all sides it is a "centimeter cube."

**Circular Mil.**—A circular mil is the area of a circle whose diameter in one mil, or one-thousandth of an inch.

*Note:* 1 mil = 0.001 inch, and 1000 mils = 1 inch.

Hence, mils ÷ 1000 = inches.

**Square Mil.**—A square mil is the area of a square whose sides are 1 mil long. A circular mil, instead of a square unit of area, is used in measuring cross-sectional area of a round wire. In Figure 76 we have drawn a circle inside of the square to show the *relation between area* which is represented by *square mils* or by *circular mils.*

Let us explain this relation in the following way: Suppose the diameter of each small circle is 1 mil, or 0.001 inch. It is seen that the length of each side of the square is 5 mils since there are 5 circles on each side. The *area of the square,* with sides measuring 5 mils, is 5 × 5, or 25 *square mils.* Now, the area of the large circle is multiplied by itself, or $d^2$. Since there are 5 small circles, 1 mil each, in the diameter of the large circle, then its diameter must be 5 mils, and the *area of the large circle* expressed in circular mils is, therefore, 5 × 5, or 25 *circular mils.* Knowing that the area of the large circle equals the sum of the areas of the 25 small circles one can say *that the area of a wire in circular mils is equal to the diameter squared expressed in mils.*

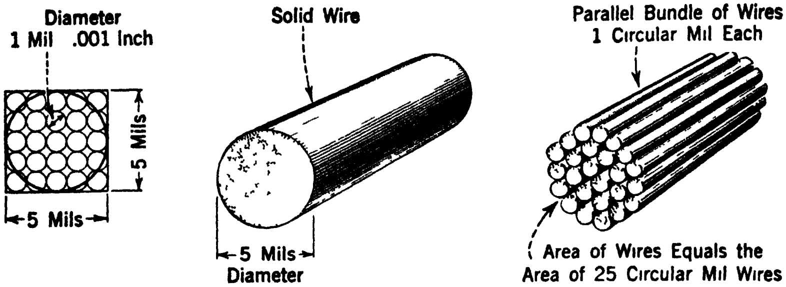


Fig. 76.—Sketches to aid in understanding the principles of wire measurements

To cite examples. If a certain wire measures 3 mils in diameter it will have a cross-sectional area of 3 × 3, or 9 mils. A wire with a diameter of 162.02 mils has an area of 162.02 × 162.02, or 26,250 circular mils. Refer to Wire Table.

Keep in mind the following difference: The area of a circle in *square mils* is equal to the diameter squared multiplied by 0.7854 (or $d^2 \times 0.7854$), whereas the area in *circular mils* is equal only to the diameter squared (or $d^2$). Since we use 0.7854 (which is a value less than 1) in our calculation to find the area of a circle but not of a square, it follows that the area of any circle is 0.7854 of the area of a square.

From this it is evident that the square mil is slightly larger than the circular mil and, hence, there will always be a greater number of circular mils in any given area than there are square mils. Therefore, to convert a circular-mil area into a square-mil area we have merely to multiply the circular-mil area by 0.7854 and the result will be in square mils.

(*A*) Area of a circle in circular mils = $d^2$

Let $d$ = diameter in mils.

(*B*) Area of a circle in square mils = $d^2 \times 0.7854$

(*C*) Since 1 circular mil = 0.7854 square mil, then

(*D*) An area in square mils = circular mil area × 0.7854.

**How 0.7854 Is Derived.**—Area of a circle = radius$^2 \times \pi$ ($\pi = 3.1416$). If a circle has a diameter of 1 mil, its radius is 0.5 mil. Hence, the area of such a circle is equal to $r^2 \times 3.1416 = 0.5^2 \times 3.1416 = 0.25 \times 3.1416$ or $\frac{1}{4} \times 3.1416 = 0.7854$.

**Meaning of the Letter (*K*) Used in Formulas.**—The letter (*K*) is used to represent the quality of a material as a conductor. A certain volume of the material must be considered, as for instance the volume of a *mil-foot.* A mil-foot is the *volume of a wire which is 1 foot long with a uniform sectional area equal to 1 circular mil.* For commercial copper the resistance of this particular volume, or 1 mil-foot, is 10.4 ohms at a temperature of 20° C. Hence, the (*K*) value for copper at this temperature is 10.4. There are different values for the constant (*K*) for various materials, depending on their qualities as conductors, as just explained, and on the temperature selected as the basis for measurement. The (*K*) value for iron is 63.35 at a temperature of 68° F.

**How to Find the Resistance of Wire.**—The resistance of a conductor varies with the kind of material used, directly as the length and inversely as the cross-sectional area. The letter (*K*) is the symbol that represents the kind of material and its resistivity, or specific resistance, as mentioned before.

**(1) To Find the Resistance of a Wire.**—Multiply the length in feet by the specific resistance (that is, the resistance per mil-foot) and divide this result by the cross-sectional area in circular mils. Writing this down in the form of an equation it would read:

$$R = \frac{K \times L}{d^2}, \quad \text{or} \quad \frac{KL}{d^2}$$

(*Note:* Multiplication sign (×) is understood between two quantities when written together. Hence, $K \times L$ and $KL$ are the same.)

The letters shown in the formula on the previous page, and what they represent, are explained as follows:

$R$ = resistance in ohms.
$L$ = length of wire in feet.
$d$ = diameter in circular mils. Therefore,
$d^2$ = circular-mil area.
$K$ = specific resistance of the material. Commercial copper at 20° C. has a specific resistance of 10.4 ohms.

**Problem:** What is the resistance of 1000 feet of copper wire having a cross-sectional area of 5000 circular mils?

*Solution:* Substituting all of the known values in the above formula, and solving, we have

$$R = \frac{10.4 \times 1000}{5000} = \frac{10{,}400}{5000} = 2.08 \text{ ohms. } \textit{Answer.}$$

**(2) To Find the Length of a Wire When the Resistance and Area in Circular Mils are Known.**—Applying the following formula:

$$L = \frac{R \times d^2}{K}.$$

**Problem:** If the size of a certain iron wire conductor is a No. 17 B. & S. gauge and its resistance is 15 ohms, what is its length?

*Solution:* Substitute the known values in the formula just given after first finding the value of $d^2$ from the wire table for a No. 17 wire. The value for $d^2$ is 2048, as given in the column marked, "Area in circular mils."

$$\text{Let } K = 63.35 \text{ for iron.}$$
$$d^2 = 2048.$$
$$\text{Hence, } L = \frac{15 \times 2048}{63.35} = \frac{30{,}720}{63.35} = 484 \text{ ft. } \textit{Ans.}$$

**(3) To Find the Circular-Mil Area of a Wire When the Length and Resistance Are Known.**—Applying the following formula:

$$d^2 = \frac{L \times K}{R}.$$

**Problem:** Suppose the length of a coil of copper wire is 2000 feet and its resistance is 20 ohms, find the circular-mil area of the wire.

*Solution:* Substitute the known values in the above formula and solve:

$$d^2 = \frac{2000 \times 10.4}{20} = \frac{20{,}800}{20} = 1040 \text{ circular mils. } \textit{Ans.}$$

**(4) To Find the Area of Square or Rectangular Conductors.**—Some conductors are made square or rectangular in shape and these are measured in square mils. Suppose a certain conductor is rectangular, then it will be a simple matter to find its area in square mils by multiplying its width by its thickness, or if the wire is square its area is found by squaring its sides. The dimensions, of course, must be expressed in mils.

EXAMPLE: If a conductor is square and 2 mils on each side its area will be 2 × 2, or 4 square mils. Or if rectangular and 2 mils on one side and 4 on the other, its area will be 2 × 4, or 8 square mils.

### (5) How to Convert Square Mils to Circular Mils and Vice Versa:

(*A*) If it is desired to change the area of a wire when given in square mils to an equivalent area in circular mils, multiply the square-mil area by 1.2732 as illustrated in problem worked out below.

PROBLEM: A flat ribbon wire is $\frac{1}{5}$ inch thick on one side and $\frac{1}{2}$ inch wide on the other. Find its equivalent area in circular mils.

*Solution:* Since the measurements are given in inches instead of mils you must first change $\frac{1}{5}$ inch and $\frac{1}{2}$ inch to mils. Thus, $\frac{1}{5} \times 1000 = 200$ and $\frac{1}{2} \times 1000 = 500$. The square-mil area is next found by taking the product of these values, or $200 \times 500 = 100{,}000$ square mils. Now multiply the square mils just found by 1.2732 as follows:

$$100{,}000 \times 1.2732 = 127{,}320 \text{ circular mils. } \textit{Ans.}$$

(*B*) If it is desired to convert the area of a wire expressed in circular mils to an equivalent area in square mils, multiply the circular-mil area by 0.7854 as shown in the following worked-out problem.

PROBLEM: Find the square-mil area of a wire having a diameter of $\frac{1}{5}$ inch.

*Solution:* First, change $\frac{1}{5}$ inch to mils, or $\frac{1}{5} \times 1000 = 200$ mils. The circular-mil area is equal to the diameter in mils squared, or $200^2$, or $200 \times 200 = 40{,}000$ C.M. (C.M. is the abbreviation for circular mils.) Now multiply the circular-mil area by 0.7854 as follows:

$$40{,}000 \times 0.7854 = 31{,}416 \text{ square mils. } \textit{Ans.}$$

**(6) How to Find the Circular-Mil Area When Diameter is Given in Inches and Vice Versa.—**

(*A*) If the diameter of a round wire is expressed in inches its circular-mil area can be found by squaring the diameter when expressed in mils. The following equation represents the relation.

Area in C.M. (circular mils) = $d^2$ (diameter in mils squared).

PROBLEM: What is the circular-mil area of a wire having a diameter of $\frac{1}{5}$ inch?

*Solution:* The first thing to do is to change $\frac{1}{5}$ inch to mils as follows: Since 1 inch = 1000 mils, then $\frac{1}{5}$ inch equals $\frac{1}{5} \times 1000$, or 200 mils. Now find the area as follows:

$$\text{C.M.} = d^2 = d \times d = 200 \times 200 = 40{,}000 \text{ circular mils.} \quad \textit{Ans.}$$

(*B*) If the circular-mil area of a wire is known and it is desired to find its diameter expressed in mils you have simply to extract the square root of the known area. Thus.

$$d = \sqrt{\text{C.M.}}$$

PROBLEM: What is the diameter in inches of a wire having an area of 4107 C.M. (circular mils)? (Area of a No. 14 gauge wire is 4106.8, as given in Wire Table.)

*Solution:* Work out the problem by finding square root of 4106, thus:

$$d = \sqrt{\text{C.M.}} = \sqrt{4107} = 64 \text{ mils, or } 0.064 \text{ inch, approximately.} \quad \textit{Ans.}$$

## PROBLEMS ON CHAPTER V

1. How may the effective length of an insulator be increased?
2. What is the square-mil area of a wire $\frac{1}{4}$ inch in diameter?
3. (*a*) Is it possible for current to flow in a wire without producing some heat and why?
    (*b*) What is an alloy and why is it used in the manufacture of certain *kinds of wire?*
    *(c) Name one alloy and give its composition.*
4. *What is the function of a resistor?*
5. *If the resistance of a certain coil is known to be 0.06 ohm, what is its resistance expressed in microhms?*

**6.** What is the difference between an insulator and a conductor?

**7.** Find the resistance of 1500 feet of copper wire having a cross-sectional area of 10,000 circular mils.

**8.** What is the difference between a fixed resistor and a rheostat?

**9.** What does the coefficient of temperature mean?

**10.** (*a*) What are the three forms of opposition or resistance in an a-c circuit?
(*b*) Is there more than one form of resistance in a d-c circuit? Explain.

**11.** (*a*) Why are there no perfect conductors?
(*b*) Why are there no perfect insulators?

**12.** Name some materials in common use as conductors and insulators, and also one or two that would be classed as partial conductors. Label them according to their respective classifications.

**13.** If the size of a certain annealed copper wire is No. 12 B. & S. gauge and its resistance is 14 ohms, what is its length?

**14.** If 1600 ft. of copper wire were used in winding a coil having a resistance of 15 ohms what would be the circular-mil area of the wire?

**15.** (*a*) If a flat ribbon wire measures $\frac{1}{6}$ inch on one side and $\frac{1}{3}$ inch on the other, what is its equivalent area in circular mils?
(*b*) What is the square-mil area of a wire having a diameter of $\frac{1}{10}$ inch?

**16.** If the resistance of a certain unit or part were 100,000 ohms what would be its equivalent value in megohms?

**17.** What does the term "$I^2R$ loss" stand for?

**18.** What is the function of a voltage divider?

**19.** (*a*) What is the term "conductance" used to express?
(*b*) If a certain conductor has a resistance of 8.5 ohms what is its conductance?

**20.** Suppose you owned a certain device that required 6 amperes of current to operate it what size wire would you use to connect the device to the power line?

# CHAPTER VI

# ELECTRICAL CIRCUITS—OHM'S LAW

AN UNDERSTANDING OF OHM'S LAW IS ESSENTIAL. HERE IT IS PRESENTED WITH WORKED-OUT PROBLEMS WHICH CLEARLY EXPLAIN THE RELATIONSHIP EXISTING BETWEEN CURRENT, VOLTAGE AND RESISTANCE IN PRACTICAL EVERYDAY CIRCUITS

IT IS quite obvious why water from a reservoir flows through a pipe. When a large quantity of water is stored in a reservoir there is a tremendous pressure exerted on the bottom, due to the weight of the water. However, if we consider different levels from the bottom upward it is well known that the pressure decreases as we approach the surface and, in fact, on the surface there is no pressure whatsoever, due to the water itself. In general, we can say that the higher the level the greater will be the available pressure from a reservoir or any tank in which water is stored. Now suppose this water supply is piped right into your home and valves are placed at convenient locations in the piping system. We all know that when the valves are closed water will not flow, although there may be water in the pipes and a high head pressure behind the water ready to make it flow. Hence, to cause the water to flow we have merely to open one of the valves and instantly the pressure acts on the water and a flow is set up through the pipes and water is seen to issue forth from an open end or faucet. It is easy to picture the flow of water in the pipes although we cannot see inside the pipes and, moreover, we understand how a certain *pressure* is responsible for the rate at which the water flows and how the oppositions or *resistances* in the piping system also govern, to a great extent, how fast or slow will be the *rate of flow*.

Although we have similar conditions of *pressure, resistance,* and *rate of flow* present in an electrical circuit, yet they are not nearly so easy to visualize as conditions which govern water flowing through pipes. However, the actions taking place in a circuit can be greatly clarified if we will think of an electric current as really something which is in motion. This is where the electron theory helps us to form a mental picture, for, according to the physicists who evolved this theory, we are to think of this something in motion (and which we call an electric current) as nothing more than countless numbers of electrons moving in a regular procession through a wire, or any conductor or medium through which current will pass. The direction in which the electrons will flow is the same as the applied electric pressure (electromotive force) which is forcing them to move. So long as pressure is applied and a circuit is completed, that is, a path furnished for the electrons to move through, they will continue to flow and to express this action, when speaking in practical terms, we say that "current is flowing."

Thus, it is evident that electromotive force is the primary cause of a flow of electric current. You can recall from your previous studies that the atoms of certain materials which are used extensively as conductors have more or less free electrons that are easily influenced and can be made to move away from or become detached from the atoms to which they normally belong by an electric pressure. Also, you should be able to recall that each electron is thought to be a tiny indivisible unit of electricity, and for this reason electrons are called "carriers of electricity." In our radio work you often hear of electrons referred to as "carriers."

The fact that wires and other materials used in the construction of circuits are supposed to possess these free electrons, or carriers, is of no value unless the electrons can be set into motion and, likewise, we could say that the fact there is water in a pipe is of no value unless it can be made to flow so that we can use it to suit our needs. Remember, then, that it is only while electrons are moving along a wire, or through a liquid, or through an electrolyte, or through a gas or other medium that we have an electric current. Consequently, it is only under this condition of progressive motion from one place to another that electrons, or carriers, constitute a current flow and are capable of performing useful work of some kind. For instance, the current is capable of producing heat, and light, and power for the operation of radio circuits and electrical machinery in general, and so on.

Anything that will increase the number of electrons moving through a conductor or anything that will hinder the electrons also will increase or decrease the *strength of the current,* as the case may be, since the moving electrons and the current are one and the same thing.

In the previous chapter it was explained that the particular quality of all materials by which they naturally tend to oppose or prevent a flow of current (of course, in varying degrees as determined by the kind of material under consideration) is known as **resistance.** Our present theory regards the differences in the resistances of various materials as being due to possible differences in the number of carriers that are available and can be detached from the individual atoms of materials. In addition, it was mentioned that heat is produced wherever there is resistance, the heat being generated no doubt by the repeated collisions between the moving electrons and atoms or molecules of a substance.

A few remarks at this time are sufficient regarding how the electrical pressure necessary to make electrons move is obtained. We are indebted to the ingenuity of man for the variety of sources of electric pressure or electromotive force which find daily application according to practical conditions. For instance, it was discovered years ago that when two dissimilar metals were immersed in an acid solution an *e.m.f.*, or *difference of potential,* would be set up between the two metals. The two metals were named *electrodes,* one being called a positive electrode and the other a negative electrode. If a metallic circuit, such as one composed entirely of wire, were suitably connected to the electrodes, the e.m.f. thus produced would cause electrons to move through the metal path and also through the liquid. This is the same thing as saying that an electric current would be set up through the entire circuit by the pressure produced at the electrodes. A device of this kind is called a wet battery. This discovery led to the development of modern types of batteries, all of which function in general on this principle.

The sources of electromotive force in common use are primary batteries, which include dry cells and wet batteries which cannot be recharged, and secondary or storage batteries which can be charged and˙ recharged, and also a-c and d-c generators, and also e.m.f.'s obtained by electrostatic and electromagnetic induction. The e.m.f. furnished by a generator is obtained by the action of rotating coils cutting through strong magnetic fields. However, in any case, let it be understood that neither batteries, generators nor any other type of apparatus you might mention are really storage plants for electric current; none of these supply electric current, they merely provide electric pressure or e.m.f., and that is why we use the expression "source of e.m.f."

**Explanations about Polarity and Direction of Current Flow in a Simple Circuit.**—In Figure 77 is shown a metal rod *ABC* connected by wiring leads to a source of power which in this case is a dry cell. For clearness the same circuit is represented in Figure 78 with symbols. The purpose of this diagram is to show that in our practical work with electrical circuits we consider that current flows through a circuit connected to battery, or generator, or other source, from a higher level which is marked + to a lower level which is marked −. To denote this direction we place arrows alongside the wiring of the circuit, or sometimes arrow-heads are placed on the wires. The circuit through which current flows outside of a battery or generator is called the "load resistance" or the "external circuit," and the path of the current within the source of power is called the "internal circuit." In practical terms, if we consider some particular location on a circuit then all points above this level are + with respect

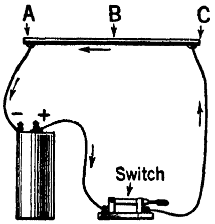


FIG. 77.—A simple electrical circuit in pictorial form used in explaining relative polarity between different points along the circuit.

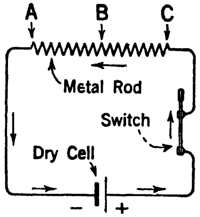


FIG. 78.—The circuit shown pictorially in Fig. 77 using symbols for the component parts.

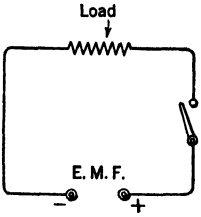


FIG. 79.—Presenting in simplest form the circuit shown in Figs. 77 and 78.

to it, and all points below this level are − with respect to the selected location. For instance, in Figures 77 and 78 the points marked *B* and *C* are both + with respect to *A*, since *A* is −, and on the other hand points marked *A* and *B* are both − with respect to *C*, since *C* is +. Furthermore, considering only points *B* and *C* with respect to each other, point *C* is + and point *B* is −, and comparing together only points *A* and *B*, point *A* is − and point *B* is +.

Sometimes the source of e.m.f. and arrows are omitted, as in Figure 79, and the terminals are marked with polarity signs + and − as shown. Note that the external resistance representing rod *ABC* is marked "load." By using Ohm's Law it is easy to determine the current flow through the rod if we know its resistance and the voltage of the dry cell. The picture diagram in Figure 80 shows a dry cell supply in a 1.5-volt flashlight lamp; the same circuit is represented by symbols in Figure 81.

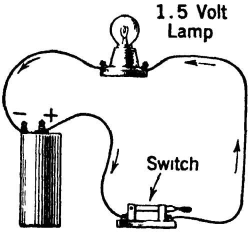


FIG. 80.—A pictorial drawing to illustrate polarity and direction of current flow.

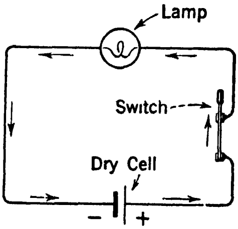


FIG. 81.—A schematic diagram of the electrical circuit shown pictorially in Fig. 80.

One of the points which seems to confuse many students is in regard to the apparent difference in the direction indicated for current flow and the direction which physicists say that electrons are supposed to move. If we say that electron movement is current flow then it would seem that when referring to this movement of electricity in terms of either *current* or *electrons* we should give them both the same direction, but this, however, is not always done in practice. For many years before the electron theory became generally accepted the diagrams of circuits appeared with current flowing from positive to negative, and for all practical purposes we can still use this designation if we wish. However, when the theory and probable occurrences in any conducting medium or circuit are considered from the electron viewpoint, we must necessarily indicate the electron movement from negative, or a point of high density, to positive, or a point of low density. Throughout our work we conform to the prevailing standard practice as follows: When explaining how a circuit functions in a very practical way in terms of current we designate the direction of current flow as from positive to negative in our diagrams, but when explaining electrical actions solely by means of electrons and the electron theory we designate the electron flow as from negative to positive.

**Important Points Regarding E.M.F. and Current Flow in an Electrical Circuit.**—Did you ever stop to consider that the eye is able to detect the motion of water only through its effect upon some other body? To find out whether or not this is true connect a glass tube between two pieces of rubber tubing and allow water to run through. If the water is perfectly clear you cannot see it moving, but if it contains dirt particles or specks of any kind, or air bubbles, you will see the particles in motion and realize that the water is carrying them along. So it is with electric current, or moving electrons. We can detect the presence of an electric current only indirectly by resulting effects, for example, by the production of heat in a conductor, or by the establishment of a magnetic field. Even magnetic lines must act upon some device or instrument such as a compass, for instance, before we realize their presence. So, if we compare electrons in motion with a liquid in motion some standard means of measuring the quantities must be adopted. With liquid we may use gallons per minute, or some other convenient unit such as a pint or a quart. In the chapter on electrical units it was explained that a coulomb per second is the unit quantity of current, or an ampere. An ampere is defined in very practical terms since it is based on the chemical action which results in the quantity of electricity depositing 0.0011118 gram of silver under certain conditions.

Now, since current flow and electron flow are the same thing and the name *ampere* is given to a definite quantity of electricity, or a *coulomb per second,* then one coulomb can be expressed as a certain number of electrons according to the modern conception that an electron is the smallest quantity of negative electricity and, therefore, is a natural unit of electricity. Dr. Robert A. Millikan measured the charge possessed by an electron and, since all electrons are alike, he computed the quantity of current flowing through a conductor per second in terms of electrons. He estimated that when one coulomb per second is flowing, then $6.06 \times 10^{23}$ electrons are flowing per second through the conductor. The expression $10^{23}$ indicates that 10 is to be raised to the 23d power, or 10 is to be multiplied by itself 23 times. This value when found and multiplied by 6.06 would give a whole number consisting of about 24 figures. We suggest that you work out the computation of Professor Millikan if you are interested and find the number of electrons in a coulomb. The progressive movement of electrons from atom to atom through a conductor or through a circuit is a very slow drift estimated at the rate of only about 1 centimeter or less per second. This movement must not be confused with the high velocity with which electrons revolve around the positive nucleuses of atoms, which is thought to be in the neighborhood of several million centimeters per second.

Before proceeding with our subject we will explain a point of similarity between a water system and an electric circuit. Let us assume at the start that water is already present in the pipes of a certain system and will not flow until the pressure is applied by *opening a valve*, and on the contrary the water stops flowing only when the pressure is not allowed to act by *closing the valve.* In an electrical circuit a switch does the work of the valve in the water system. Now, let us assume that in our electrical circuit the path of the current is entirely through metallic wires and the only things that move are the electrons and these are already present in the wires. Immediately upon *closing the switch* in the electric circuit *e.m.f. is applied* and electrons move in a certain direction through the circuit, or *current flows.* On the other hand, if the switch is opened, or if a wire is disconnected, or breaks somewhere, the *e.m.f. is discontinued* and the electrons cease moving through the circuit, or *current stops flowing.*

**Electromotive Force, Resistance and Current Relations.**—What we wish to call to your attention is that throughout our discussions three factors are taken into account whenever we say that "current is flowing." The three factors to be remembered and which we have summarized below are (1) **electromotive force,** (2) **resistance,** and (3) **current.**

(1) The electromotive force or pressure must be obtained first to make the electrons move. *The amount of this e.m.f. is measured in the unit "volt."* Therefore, we must have an *e.m.f.* of a certain number of volts applied to any given circuit, or to some portion of it in order to set up a flow of current.

(2) Every circuit has a certain amount of resistance depending mainly upon the materials used. It is this resistance that tends to limit the current to a certain value when an e.m.f. of a given voltage is applied to either an entire circuit, or to some part of it. *The resistance is measured in the unit "ohm."*

(3) The strength of the *current is measured in the unit "ampere"* and it depends upon the amount of resistance that must be overcome by a given e.m.f. expressed in volts.

Our problem now resolves itself into a study of different kinds of circuits and, also, the factors that affect the strength of the current flowing throughout any active circuit or through only some part of it. There are three facts or considerations, as listed below, with which everyone should be familiar.

FIRST CONSIDERATION.—Since the e.m.f., or difference of potential expressed in volts, is one of the factors that determines the amount of current, then we should be able to calculate the amount of e.m.f. to be applied to a circuit or part of a circuit to obtain a required current.

SECOND CONSIDERATION.—Since the other factor that determines the amount of current is the resistance, expressed in ohms, then we should be able to calculate the resistance of any circuit or part thereof in order that a given voltage will produce a required current.

THIRD CONSIDERATION.—Since the ultimate thing that we are concerned with is the strength of the current we can very easily determine how to get a current of a required intensity or strength provided we know how to figure the voltage and resistance relations.

From all that we have said about this subject thus far it is apparent that one must possess a thorough understanding of *current, voltage,* and *resistance* relations to work intelligently with electrical circuits. There is a very important and definite relationship existing between the three factors we have just outlined which was discovered by Dr. George S. Ohm, a famous physicist, after a series of experiments in the year 1826. The remainder of this chapter deals entirely with Ohm's Law and its practical application to various kinds of electrical circuits. We cannot emphasize the fact too strongly that an understanding of current strength in circuits is absolutely essential and, therefore, the following work should be carefully studied.

## OHM'S LAW

*The general law formulated by Ohm stated that the intensity or strength of the electric current varies directly with the difference of potential across a conductor, and inversely as the resistance of the conductor.*

When this relation is written in the form of an equation it appears thus:

$$I = \frac{E}{R}, \text{ or it may be written } I = E \div R.$$

In the above formula expressing Ohm's Law the symbol $I$ represents the current expressed in amperes, $E$ represents the difference of potential expressed in volts, and $R$ represents the resistance expressed in ohms. The formula as stated tells us that the current in a given circuit is equal to the electromotive force impressed on the circuit divided by the resistance of the circuit. Also, the same formula tells us that the current flowing through a certain part or portion of a circuit is equal to the electromotive force applied to that part divided by the resistance of that part. This double application of Ohm's Law is explained fully in subsequent paragraphs.

If you read Ohm's Law carefully you will notice that there are two separate parts or considerations to it, and that each one concerns the strength of the current. We will point out these parts to you and explain them in detail.

**Part 1.**—The first part of Ohm's Law has to do with e.m.f. or voltage, and it says in effect that the current depends upon or varies directly with the e.m.f. This means that *providing the resistance of a circuit remains unchanged* (or remains constant, which is the same thing) and the voltage is increased by a certain amount the current will also increase in the same proportion that the voltage is increased and, on the other hand, if the voltage is lowered by a certain amount the current will diminish in the same ratio. To explain this ratio we will cite several examples.

The following examples show the effect on the current when the voltage is increased. If the voltage applied to a given circuit is doubled, the current then forced through the circuit by the higher e.m.f. will be exactly twice what it was before the voltage was changed. Hence, if we increase the voltage applied to a given circuit six times the current strength will increase six times, and likewise if we reduce the voltage by a certain amount, or let us say, by one-third, then the current strength will decrease one-third. Thus, it is readily seen that if a current of 2 amperes flows through a circuit under an applied e.m.f. of 6 volts and we raise the voltage to 12 volts the current will rise to twice its former value, or to 4 amperes.

The following is an example showing the effect on the current when the voltage is reduced. If a current of 6 amperes flows in a circuit with 90 volts applied and we reduce the 90 volts to 45 volts, that is, reduce the e.m.f. one-half, the current then will diminish to a value of $\frac{1}{2}$ of 6, or to 3 amperes. All of the examples just given illustrate what is meant by *direct proportion.* Bear in mind that the proportion stated is between the voltage and current since in each of these examples the resistance of the circuit is assumed to remain unaltered.

**Part 2.**—The second part of Ohm's Law has to do with the resistance, and it says that the current varies inversely with the resistance. This means that *providing the voltage of a circuit remains unchanged, or remains constant, and the resistance is increased by a certain amount, it will cause the current to decrease in the same proportion.*

For example, if in a certain circuit the resistance is made twice as great as previously. the current will drop to one-half its former value, or if the resistance is made five times as great the current will decrease to one-fifth its former value. To give another example, suppose a circuit consists of only one coil of wire having a resistance of 10 ohms and a current of 3 amperes flows at a given voltage supplied by a storage battery. Now suppose we double the resistance by connecting another similar coil in series with the first one, or in such a way that the same current flowing through one coil must also pass through the other in completing the circuit. By the addition of the second coil we have increased the opposition presented to the same e.m.f. just twice what it was when only one coil was used. Naturally, we would expect the current strength to reduce to a value ½ of 3, or to 1.5 amperes, and this is exactly what would happen, or in other words, each coil would now carry a current of 1.5 amperes.

The following is an example of the effect on the current when the resistance is decreased. If a certain battery sends 3 amperes through a circuit consisting entirely of one kind of wire of uniform size, and we then disconnect the battery and remove half of the wire, this will reduce the resistance one-half, and if now we reconnect the shorter wire and operate the circuit with the same e.m.f. or voltage as before the current strength will increase to 6 amperes. You see that after we reduced the opposition or resistance one-half, the same voltage supplied by the battery was capable of setting up a current twice as strong through the circuit. The foregoing examples in Part 2 comparing resistance and current values illustrate what is meant by *inverse proportion* or opposite relation.

**In Regard to Applying Ohm's Law to an Entire Circuit or Part of a Circuit.**—Remember, when you come to use Ohm's Law, or $I = E \div R$, that either an entire circuit or some portion of a circuit can be considered in applying this formula. In either case the relations given in the formula hold true and work out satisfactorily, provided you substitute the proper values for the different quantities as represented by the letters, $I$, $E$, and $R$. What we wish to warn you is not to confuse the voltage applied to an entire circuit with the voltage applied to a single part, or to confuse the resistance of an entire circuit with the resistance of a single part, and try to use these unrelated values in the same formula.

This is made clear in (*A*) and (*B*) following. To avoid the possibilty of making mistakes merely requires reasoning on your part.

> (*A*) *When we consider an entire circuit,* the $E$ in the formula represents the combined differences of potential throughout the circuit; $R$ represents the combined or total of all resistance that constitutes the circuit; and $I$ represents the total current that flows through every resistance. It is to be noted that the combined difference of potential which we refer to here is usually spoken of as the "voltage applied to the circuit."
>
> (*B*) *When we consider only a part of a circuit,* the $E$ in the formula represents only the difference of potential across the part in question, the $R$ is the resistance of that part only, and $I$ is the current flowing through the part.

**Ohm's Law May Be Written in Three Forms which Express the Same Relationship.**—There are three forms in which Ohm's Law can be written to simplify the working out of problems, and although each form appears different yet all are derived from the general law, $I = E \div R$, and therefore all forms express similarly the exact relation existing between current, voltage, and resistance. When numerical values are substituted for the symbols or letters the values bear a fixed ratio to one another, and mathematically it can be said that the current strength in amperes in a circuit is the ratio which the pressure in volts bears to the resistance in ohms.

The symbols and what they stand for and the units are all given in the following three forms in which Ohm's Law can be stated.

| | | |
|---|---|---|
| (1) $I = \frac{E}{R}$ | (2) $E = IR$ | (3) $R = \frac{E}{I}$ |
| or, $I = E \div R$ | $E = I \times R$ | $R = E \div I$ |
| or, current $= \frac{\text{e.m.f.}}{\text{resistance}}$ | e.m.f. = current × resistance | resistance $= \frac{\text{e.m.f.}}{\text{current}}$ |
| or, amperes $= \frac{\text{volts}}{\text{ohms}}$ | volts = amperes × ohms | ohms $= \frac{\text{volts}}{\text{amperes}}$ |

(1) We use the formula numbered (1) when we know the voltage and resistance, but not the current, and wish to determine the current. This formula states that the current is equal to the voltage divided by the resistance.

(2) We use the formula numbered (2) when we know the current and resistance, but not the voltage, and wish to determine the voltage. This formula states that the voltage is equal to the current multiplied by the resistance.

(3) We use the formula numbered (3) when we know the current and the voltage, but not the resistance, and wish to determine the resistance. This formula states that the resistance is equal to the voltage divided by the current.

In other words, if we know two of the quantities we can put these values in their proper places in the formula and always find the value of the third or unknown quantity by working out the formula, which is done by simple arithmetic. After you once know the proper values to substitute for the letters or symbols in whichever formula you intend to use, then you merely multiply or divide as the case may be according to the formula. Regardless of how complicated a circuit might appear to you, it can always be divided into small sections or individual parts and Ohm's Law can be applied to each of these parts in succession to find the current, voltage and resistance distribution until a full knowledge of the circuit is obtained.

There is another point to be mentioned at this time in regard to the electrical units used in the formulas. If a current value is measured in milliamperes this sub-multiple must be converted into the unit *ampere* and the value in *amperes* is used in the formula. Also, if a resistance value is given in microhms which is a submultiple, or megohms which is a multiple of an ohm, these must be converted to the *unit ohm* and the value in *ohms* is used in the formula. In ordinary work voltage measurements are usually given directly in *volts*.

**An Easy Way to Remember Ohm's Law.**—Many students have asked the question, " How can I remember the three different forms in which Ohm's Law may be written? " In answer to this question we have given a very simple method of showing the relationship of the three quantities $I$, $E$ and $R$ by first writing down the symbols as in Figure 82. The circle is put around the letters merely to help you in visualizing the arrangement of the letter groups.

Now, assume that you know the values of *E* and *R* and wish to find out what *I* equals, then with your finger cover over the *I* in Figure 82 and you will see that *E* appears above *R*, which means that *E* must be divided by *R* in order to determine what *I* equals. So, we write down the equality sign between *I* and *E* over *R* and, hence, we have the form shown in Figure 83.

This time assume that you know the values of *I* and *R* and wish to find out what *E* equals, then with your finger cover the *E* in Figure 82 and it is at once apparent that *I* is alongside of *R*, which means that *I* must be multiplied by *R* to obtain what *E* equals. Hence, after placing the equality sign after *E* we have the second form shown in Figure 84.

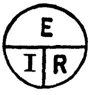


FIG. 82.

$$I = \frac{E}{R}$$

FIG. 83.

$$E = I \times R$$

FIG. 84.

$$R = \frac{E}{I}$$

FIG. 85

FIGS. 82, 83, 84 and 85.—A simple and easy method for showing how to write Ohm's Law in its three forms.

Again, assume that you know the values of *E* and *I*, but this time you wish to find out what *R* equals, then cover over the *R* in Figure 82 and you will notice that *E* is written above *I*, which means that *E* is to be divided by *I* to obtain the required resistance. Hence, after writing the equality sign after *R* we have the third form shown in Figure 85. Thus, you see that it is easy to write these formulas correctly by simply putting an equality sign after the quantity you wish to determine, or the "*unknown quantity*" as we usually refer to it. Then by covering over the unknown quantity with your finger as shown in Figure 82 you have the two remaining quantities, or "*known quantities*," correctly arranged as already explained.

**A Simple Electric Circuit.**—The pictorial diagram in Figure 86 shows an electric circuit consisting of a coil, a switch to open and close the circuit, an ammeter, and dry cells to furnish the necessary e.m.f. or pressure. It illustrates how a flow of current sets

**up magnetic flux and how the forces can be indirectly visualized by the effect on the pointers of the ammeter and compass.**

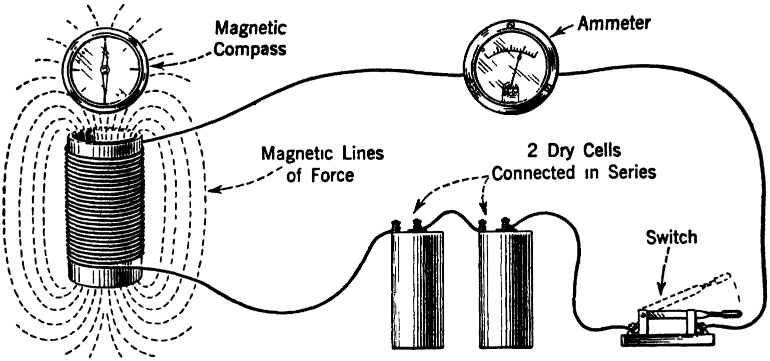


FIG. 86.—The lay-out of an electrical circuit showing how a flow of current sets up magnetic flux which may be detected with the aid of a pocket type compass.

## PRACTICAL PROBLEMS APPLYING OHM'S LAW FORMULA IN ITS THREE FORMS

(1) **To find current** when resistance and voltage are known apply the following formula:

$$\text{(No. 1)}\quad I = \frac{E}{R} \quad \text{or,} \quad I = E \div R.$$

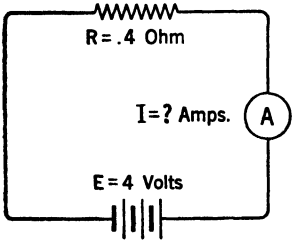


FIG. 87.

EXAMPLE: What is the current in the circuit in Figure 87 when the resistance is 0.4 ohm and an e.m.f. of 4 volts is applied?

Let $E = 4$ volts

$R = 0.4$ ohm

*Solution:* Substitute the known values in formula and solve,

$I = \frac{E}{R}$ or, $I = \frac{4}{0.4}$, hence, $I = 10$ amperes. *Ans.*

**(2) To find voltage** when current and resistance are known apply the following formula:

$$\text{(No. 2)}\quad E = IR \quad \text{or,} \quad E = I \times R$$

EXAMPLE What voltage is required to set up a current of 10 amperes in the circuit in Figure 88 when its resistance is 0 4 ohm?

Let $I = 10$ amperes

$R = 0\ 4$ ohm

*Solution* Substitute the known values in formula and solve,

$E = I \times R$ or, $E = 10 \times 0\ 4$,

hence, $E = 4$ volts *Ans*

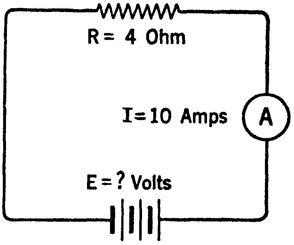


FIG 88

**(3) To find resistance** when current and voltage are known apply the following formula.

$$\text{(No 3)}\quad R = \frac{E}{I} \quad \text{or,} \quad R = E \div I.$$

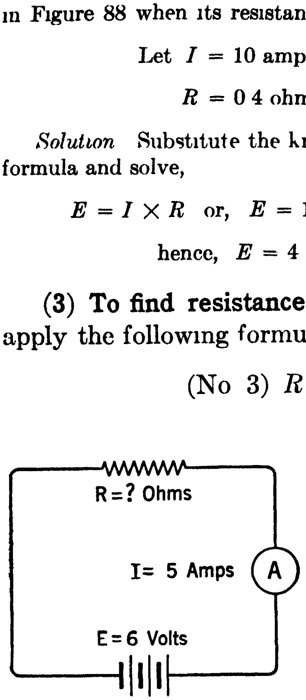


FIG 89

EXAMPLE What is the resistance of the circuit in Figure 89 when an e m f of 6 volts produces a current of 0 5 ampere?

Let $E = 6$ volts

$I = 0\ 5$ ampere

*Solution* Substitute the known values in formula and solve,

$R = \frac{E}{I}$ or, $R = \frac{6}{0\ 5}$, hence, $R = 12$ ohms *Ans*

**Potential Drop: Also Known as Voltage Drop, Fall of Potential, and Potential Drop Along a Conductor.**—In Figure 90 we have grouped three resistances in series to provide only one path for the current to flow from the positive to the negative terminals of the battery Suppose these resistances are of different values, then each one will present a different amount of opposition to the flow of current We know that the current flow will be governed by the opposition which their *combined* resistances offer to the e.m.f. of the battery. If $R_1$, $R_2$, and $R_3$ were 2, 3, and 4 ohms, respectively, then the total resistance of the circuit would be their sum, or 9 ohms, provided we neglect to consider the resistance of the wiring leads and the internal resistance of the battery. It requires a certain portion of the battery voltage to force current through $R_1$, and this amount could be measured by connecting a voltmeter between points $A$ and $B$ along the circuit. Also, it requires a certain amount of the battery voltage to force current through $R_2$, which could also be measured by means of a voltmeter connected between points $B$ and $C$, and similarly the e.m.f. applied across $R_3$ could be determined by means of a voltmeter connected between $C$ and $D$. The pressure or e.m.f. required across the individual resistances is known as the voltage drop or potential drop across that part. In technical terms, voltage drop is called the "$IR$ drop." Just what is meant by this *distribution of the applied e.m.f.*, resulting in voltage drops throughout the different portions of any circuit in overcoming the resistance of the circuit, can be shown by a hydraulic analogy. Bear in mind that the *difference of potential between any two points is a measure of the pressure*, and is also called *drop in potential* for that part of the circuit included between the two points in question. It is this pressure that sets up a flow of current between these points.

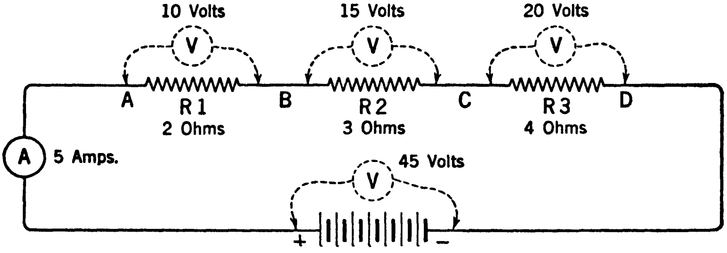


FIG. 90.—Voltmeter readings indicate the amount of the potential drop throughout portions of the circuit The terms "fall of potential" and "voltage drop" mean the same as "potential drop"

It is known from common experience that water stored in a tank as in Figure 91 exerts a pressure at the bottom which, let us say in this case, is 100 lbs. Three pipes of different length and size are joined together so that any given amount of water flowing out of the tank must pass through each section of the pipe and flow out at the open end. The same quantity of water must flow out of the pipe that enters it at the tank end. To show that a certain amount of the 100-lb. pressure is used in forcing the water through the various sections we have placed pressure gauges at certain intervals along the pipe line. We could have a condition where the second gauge reads 98 lbs., indicating that it took 2 lbs. of pressure to send water through the first length of pipe marked *A*, and if the third gauge reads 95 lbs. we would know that it took 3 lbs. of pressure to send water through the second length marked *B*, and if the fourth gauge registers 90 lbs. it would show that it took 5 lbs. to send water through the third length marked *C*, assuming *C* to be of long length. Hence, we can conclude that in this water system the pressure dropped from 100 to 90 lbs. in overcoming the various resistances or oppositions presented, or in other words there is a loss or *difference in pressure* between the extreme points of the pipe line amounting to 10 lbs. This illustrates how the *pressure is distributed through the pipe line* and the gauges indicate the amount of pressure acting at the points where they are located.

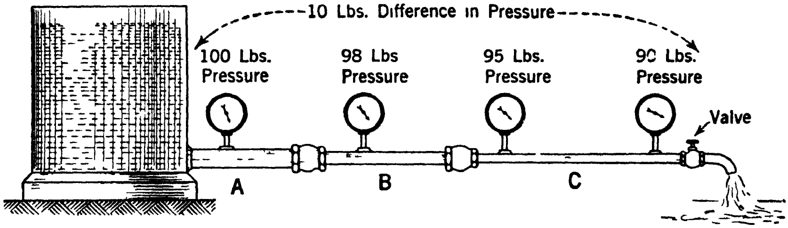


FIG. 91.—A water tank analogy for demonstrating fall of pressure which in the electrical circuit is called "fall of potential."

**Various Ways of Arranging the Component Parts of a Circuit.**—The conductors or pieces of electrical equipment that constitute a circuit can be grouped in various ways, but in general, the connecting together of two or more parts can be classified under two arrangements, namely, a "**series**" and a "**parallel**" arrangement.

There are also numerous circuits so constructed that they form a **combination of series and parallel arrangements.**

**Series Circuits.**—When all the resistances or parts are grouped in such a way that the current has only one path through which it can flow then a circuit of this kind is said to be a *series circuit.*

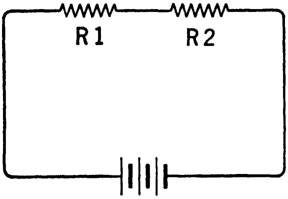


FIG. 92.—A series circuit consisting of two resistances and a source of e.m.f.

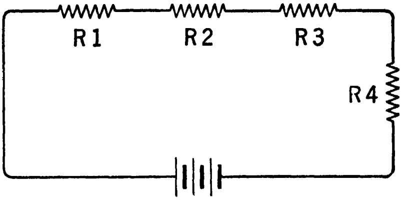


FIG. 93.—A series circuit consisting of four resistances and a source of e.m.f.

Figure 92 is a conventional diagram of a series circuit showing two resistances, $R_1$ and $R_2$, connected to a battery. Figure 93 shows four resistances, $R_1$, $R_2$, $R_3$, and $R_4$, connected in series and to the terminals of a battery. The circuit in Figure 94 is drawn especially to illustrate voltage, current and resistance relations. It shows the filaments of three vacuum tubes connected to a battery of suitable voltage through a rheostat which is used to regulate the e.m.f. applied to the filament terminals.

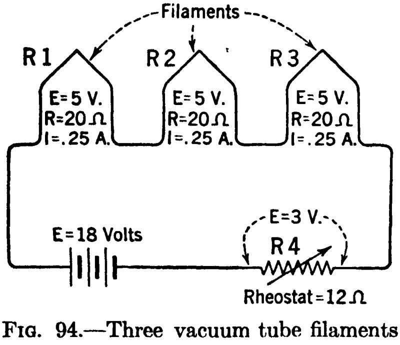


FIG. 94.—Three vacuum tube filaments and a rheostat are drawn in series with one another and connected to a battery to illustrate the relation existing between the voltage, current and resistance in such a circuit.

In a series circuit *voltage, current,* and *resistance* relations are as follows:

*Voltage.*—The total voltage of a series arrangement of resistances is equal to the sum of the voltage drops, or differences of potential across the separate resistances. For example, if in Figure 94 the potential difference across each filament were 5 volts, thus giving 15 volts across the three, and the battery were 18 volts, then the drop across the rheostat would be 3 volts. That is to say, the sum of the various voltage drops equals the e.m.f. at the source, or, in this instance, the 18 volts furnished by the battery.

*Current.*—If the current through one of the filaments in Figure 94 is 0.25 ampere then this same value of current must pass through the other two filaments, and through the rheostat and battery as well, since there cannot be any greater current in one portion of a series circuit than in another.

*Resistance.*—Furthermore, if the resistance of each filament were alike, or 20 ohms each, and the rheostat 12 ohms, then the combined resistance of the circuit external to the battery would be $20 + 20 + 20 + 12$, or 72 ohms.

The student should understand that the same current flows through all portions of a series circuit, although the resistance of one part may be higher or lower than that of another part. This is easy to understand if one will keep in mind the action of the water flowing through the piping system shown in Figure 91. It is obvious that the same quantity of water passing through one section of pipe must also pass through all the others, and so it is with the amount of current passing through the parts of a series circuit. The same current entering a certain portion must leave an adjoining portion—no more or less.

**Parallel or Multiple Circuits.**—When two or more resistances or pieces of electrical apparatus are connected in such a combination that the current is divided among them and flows in all of the branches the circuit is called a *parallel* or *multiple circuit.* A circuit of this kind is often called a divided circuit. The *voltage, resistance* and *current* relations are as follows for parallel grouping of parts.

*Voltage.*—The difference of potential, or voltage drop, across each branch of a parallel circuit is the same as the voltage across the whole combination. The voltage between points $A$ and $B$ in Figure 95 is 6 volts since the voltage across the battery is 6 volts, and therefore the e.m.f. applied to each of the three resistances, $R_1$, $R_2$, and $R_3$, is 6 volts.

*Current.*—In the circuit in Figure 95 the total current flows from the positive pole of the battery to point $A$, where it divides into three currents, each of which is smaller than the main or total current. The current in each resistance is inversely proportional to the three resistances. At point *B* the three small currents unite as one current again and, therefore, the sum of the three small currents must equal the total current flowing from *B* to the negative pole. Hence, the current in a parallel circuit equals the sum of all the currents in the different branches. To find current in a branch apply Ohm's Law to that branch.

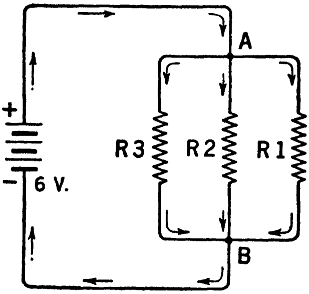


FIG. 95.—A circuit in which the resistances are in parallel or multiple arrangement.

*Resistance.*—The schematic diagrams in Figures 96 and 97 show, respectively, two and four resistances connected in parallel arrangement and to the terminals of a battery. If all the resistances were equal in value the same amount of current would flow in each, but if they were unequal then the current will be proportionately divided and, naturally, the highest current value will flow in the resistance offering the least opposition or the one with the lowest resistance, whereas the smallest current will flow in that resistance having the highest opposition or the largest resistance.

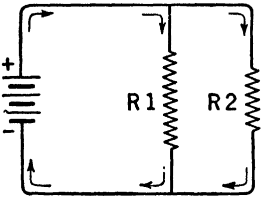


FIG. 96.—Two resistances connected in parallel and to a source of e.m.f.

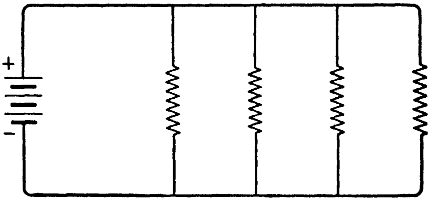


FIG. 97.—Four resistances connected in parallel which are also supplied with e.m.f. from a battery.

We then can say that the part of the total current that flows in each resistance will depend upon the relative resistance of that particular resistance to the other resistances. By working out some of the problems given in this chapter on parallel grouping of parts you will notice that the combined resistance of parts or conductors in parallel is always less than that of the smallest resistance in the group. This is accounted for by the fact that the current has more paths through which to flow, and, therefore, a greater total current must be set up by the e.m.f. of the source than if the same resistances were connected in series.

**Total Resistance of a Parallel Combination.**—This can be determined by the conductance or reciprocal method, which is explained in following paragraphs. There is another method which may prove convenient to students in calculating parallel circuit resistance, the method being clearly illustrated by the two formulas given below. Employ the formula on the left for two resistances in parallel, and the one on the right for three resistances.

$$R = \frac{R_1 \times R_2}{R_1 + R_2} \qquad R = \frac{R_1 \times R_2 \times R_3}{R_1R_2 + R_2R_3 + R_1R_3}.$$

**How to Find Joint Resistance of Resistances in Parallel by Conductance Method.**—The combined resistance of any number of unequal resistances when connected in parallel arrangement can be found by the conductance method as explained in the chapter on "Resistance." The rule is: The conductances of the separate branches through which the current flows are added to give the joint or total conductance of the combination, and the joint resistance of this combination will be the reciprocal of the sum thus found. The circuit in Figure 95 will be used in working out an example by this method. Let the three resistors joined in parallel have resistances of 3, 6, and 9 ohms, respectively.

The conductance of this combination is found by simply selecting the least common denominator, or 18, in order to obtain the sum of the fractions, thus.

$$\tfrac{1}{3} + \tfrac{1}{6} + \tfrac{1}{9} = \tfrac{6}{18} + \tfrac{3}{18} + \tfrac{2}{18} = \tfrac{11}{18} \text{ mho.}$$

Now invert the conductance $\tfrac{11}{18}$ to get the joint resistance, or

$$\tfrac{18}{11} = 1.63 \text{ ohms.} \quad \textit{Ans.}$$

Notice that the following formula combines the two steps required in the foregoing explanation *to obtain the total resistance of resistances in parallel,* or

$$R \text{ (total resistance)} = \cfrac{1}{\cfrac{1}{R_1} + \cfrac{1}{R_2} + \cfrac{1}{R_3}, \text{ etc.}}$$

It is well to mention that to express the meaning of this formula in words you would say that the total resistance of a number of resistances connected in parallel is the reciprocal of the sum of the reciprocals of the different resistances through which the current flows. To illustrate the use of this formula we will substitute the different resistance values in the same example explained above using Figure 95, and we would then have

$$R = \cfrac{1}{\cfrac{1}{R_1} + \cfrac{1}{R_2} + \cfrac{1}{R_3}} = \cfrac{1}{\cfrac{1}{3} + \cfrac{1}{6} + \cfrac{1}{9}} = \cfrac{1}{\cfrac{6}{18} + \cfrac{3}{18} + \cfrac{2}{18}} = \cfrac{1}{\cfrac{11}{18}} =$$

$$1 \div \tfrac{11}{18} = 1 \times \tfrac{18}{11} = 1.63 \text{ ohms. } \textit{Ans.}$$

**Series and Parallel Groupings of Conductors.**—To aid the student in calculating the respective resistances of the circuits in Figures 98, 99, and 100 we have indicated in the diagrams the combined resistance of each parallel group, and after these are once known and each treated as a single resistance it is merely a matter of adding up all the resistances as you would for any series circuit.

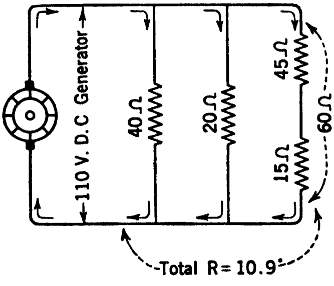


FIG. 98.—An electrical circuit in which resistances are grouped in series and parallel.

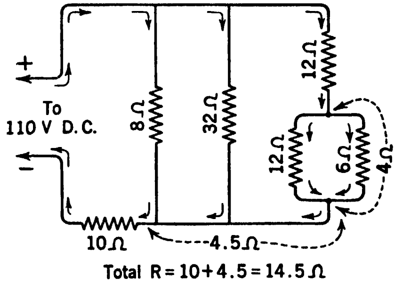


FIG. 99.—Another electrical circuit showing a series and parallel grouping of resistances.

The circuit in Figure 101 shows the filaments of three vacuum tubes connected in parallel so that each will be supplied with the same voltage from the battery through a rheostat. The same circuit is shown in another form in Figure 102 in order to indicate by

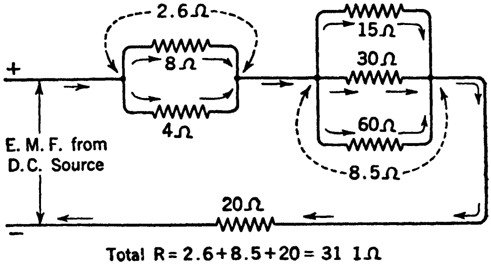
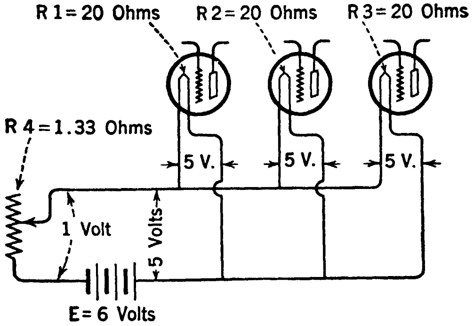


Fig. 100.—A circuit consisting of a combination of resistances connected in series and parallel.

arrows the path of the main current to *B* and how at this point the current divides into smaller currents which pass through the three filaments $R_1$, $R_2$, and $R_3$, and these currents unite at point



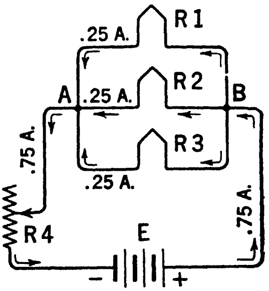


Fig. 101.—The three vacuum tube filaments and the rheostat (variable resistance) $R_4$ form a series and parallel grouping of resistances.

Fig. 102.—A schematic diagram of the circuit shown in Fig. 101.

*A* to form the main current which continues on through $R_4$ to battery *E*. The circuit in Figure 103 is the same circuit reduced to simple schematic form, using resistance symbols to make it easy to read.

**First Step.**—The first thing is to determine the total resistance of the circuit in Figure 101 or its equivalent in Figure 103. Remember that the rheostat $R_4$ is in series with the three resistances $R_1$, $R_2$, and $R_3$, which are in parallel. To find the total resistance obtain the resistance values from the diagram, Figure 101 and substitute them in the following formula; solving we have

$$R = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}} + R_4 = \frac{1}{\frac{1}{20} + \frac{1}{20} + \frac{1}{20}} + 1.33 =$$

$$\frac{1}{\frac{3}{20}} + 1.33 = \tfrac{20}{3} + 1.33 = 6.66 + 1.33 = 7.99 \text{ ohms,}$$

total resistance. *Ans.*

The first part of the above equation, namely, that part preceding $R_4$, shows how to find the joint resistance of $R_1$, $R_2$, and $R_3$ in parallel. This value, or 6.66 ohms, is added to $R_4$, or 1.33 ohms, to obtain the total resistance of the entire combination, or 7.99 ohms.

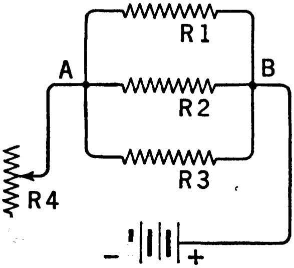


FIG. 103.—This shows the circuits in Figs. 101 and 102 using resistance symbols for the vacuum tube filaments.

The following shows how the reciprocal 1 over the fraction $\frac{3}{20}$ is worked out:

WORK: $\frac{1}{\frac{3}{20}}$ means $1 \div \frac{3}{20}$, or $1 \times \frac{20}{3}$, or $\frac{20}{3}$, which equals 6.66.

**Second Step.**—The current through each tube in Figure 101 is regulated by proper adjustment of the rheostat and is found by applying Ohm's Law. Since the resistance of each filament is alike (or 20 ohms) and the same e.m.f. (or 5 volts) is applied to each one, then the same value of current will flow in each filament, or $I = E \div R$ or $5 \div 20 = 0.25$ ampere. By adding up the different currents we get the total current flow, or $0.25 + 0.25 + 0.25 = 0.75$ ampere. *Ans.*

**Third Step.**—The following method is used in determining the resistance necessary for $R_4$ in Figure 101 to give a potential drop of 1 volt. Knowing that the total current flows in $R_4$ and the e.m.f. across it is 1 volt we have only to apply Ohm's Law to find this resistance, or

$$R = \frac{E}{I} \text{ or, } R_4 = \frac{1}{.75} \text{ or, } R_4 = 1 \div .75 \text{ or, } R_4 = 1.33 \text{ ohms. } \textit{Ans.}$$

**Series Connection of Three Resistances.**—The following example illustrates how to find the *total resistance* and method of applying Ohm's Law to find the *value of the current* and *voltage drop* across different portions of a series circuit.

Suppose for this problem we join, with suitable connections, three lengths of different kinds of wire in series with one another and attach a 12-volt battery to maintain a current through the different wires as in Figure 104.

**First Step.**—The first thing to do is *to determine the total resistance.*

Let $R_1$ = 3 ft. nickel alloy wire = 50 ohms.

$R_2$ = 8 ft. German silver wire = 100 ohms.

$R_3$ = 4 ft. galvanized iron wire = 2 ohms.

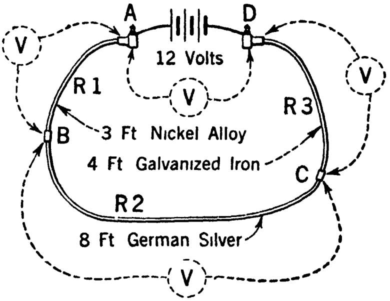


FIG 104.

The total resistance of the circuit is the sum of the three resistances,

or $\quad R \text{ (Total Resistance)} = R_1 + R_2 + R_3$

or $\quad R \text{ (Total Resistance)} = 50 + 100 + 2$

hence $\quad R \text{ (Total Resistance)} = 152 \text{ ohms.}$

**Second Step.**—The next step is *to determine the value of the current.* The current through each of the conductors depends upon their combined resistance, which is the total resistance of the circuit, or 152 ohms, and upon the amount of e.m.f. or voltage which forces the current through, which in this case is 12 volts. Apply the formula and solve.

$$I = \frac{E}{R}$$

or $$I = \frac{12}{152}$$

hence $$I = 0.078 \text{ ampere.}$$

**Third Step.**—*How to find the voltage drop across each wire.*—If a voltmeter were connected successively between all the points shown by dotted lines it would indicate how the pressure supplied by the battery is distributed through different portions of the circuit or, in other words, the voltmeter would tell us the voltage of the battery and also how much voltage was required to send current through each length of wire. It is only necessary to apply Ohm's Law in each case. Since there is only one path for the current we know that the strength of the current in each wire is the same, or 0.078 ampere, and also knowing the resistance of each wire we can from these known values determine the voltage applied across each wire (that is to say, find the voltage drop across each wire) as follows:

$E = I \times R$. or $E = .078 \times 50 = 3.9$ volts drop across $R_1$, or between $A$–$B$.
$E = I \times R$, or $E = .078 \times 100 = 7.8$ volts drop across $R_2$, or between $B$–$C$.
$E = I \times R$, or $E = .078 \times 2 = .156$ volt drop across $R_3$, or between $C$–$D$.
11.856 volts, or approx. 12 volts.

The sum of all the voltage drops, or differences of potential throughout the circuit, equals the e.m.f. of the battery measured between points $A$–$D$.

(*Note:* If the computation were carried out to more decimal places a result nearer 12 volts would be obtained.)

**Applying Ohm's Law When Internal and External Resistance Are Both Considered.**—It is to be understood that when an e.m.f. from some source is applied to a circuit a certain part of this e.m.f. is expended in sending current through the internal resistance of the source, that is, through a battery or through the windings of a generator for example, leaving the remainder of the e.m.f. to force current through the external or load resistance. Thus, the e.m.f. applied to the series circuit in Figure 105 is used to drive current through both the three external or load resistances and within the battery itself. Accordingly, the equation for Ohm's Law in this case becomes

$$I = \frac{E}{R + r}$$

where $R$ = external resistance in ohms.

and $r$ = internal resistance in ohms.

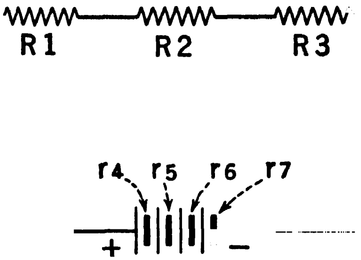


FIG. 105.

**First Step: Find Total Resistance.**—To work out a problem of this kind let us assume that in Figure 105 a 6-volt battery, consisting of 4 dry cells, is used and the resistance of $R_1$ is 2 ohms, $R_2$ is 6 ohms, $R_3$ is 4 ohms, and the internal resistance of each cell is 0.2 ohm. Thus, in this series circuit the *total resistance* is equal to the sum of the individual resistances including both external and internal resistances, or

$$R \text{ (Total Resistance)} = R_1 + R_2 + R_3 + r_4 + r_5 + r_6 + r_7.$$

Now substitute the known resistance values in the above formula and solve

$$R \text{ (Total Resistance)} = 2 + 6 + 4 + .2 + .2 + .2 + .2$$

hence

$$R \text{ (Total Resistance)} = 12.8 \text{ ohms.}$$

**Second Step: Find Current.**—The next step is to find the current by using Ohm's Law, $I = E \div R$, thus: If the voltage of each cell is 1.5 volts the total e.m.f. is 4 × 1.5 or 6 volts. Hence, if $R$ is 12 ohms and $r$ is 0.8 ohm it makes the total resistance 12.8 ohms, and the current which would then flow would be 6 ÷ 12.8, or 0.46 ampere.

**Third Step: Find Voltage Drops.**—The next thing to do is to determine the different *voltage drops* across $R$ and $r$ from the equation $E = I \times R$. First calculate the part of the e.m.f. of the source which is expended in driving current through the external resistance, or $I \times R$, or $0.46 \times 12$, which equals 5.52 volts. Now find the remainder of the e.m.f. which is applied to the internal resistance, or $I \times r$, or $0.46 \times 0.8$ which equals 0.368 volt.

Since Ohm's Law was applied to each case above we have $E = (I \times R) + (I \times r)$. Therefore, if we take the sum of the two parts in which the e.m.f. is applied, or $5.52 + .368$, it will equal the voltage of the battery, or approximately 6 volts. In most of our practical work we generally neglect the internal resistance of the source since it is usually comparatively low and hence we consider only the load or external resistance.

## DIFFERENT METHODS OF MEASURING RESISTANCES BASED ON APPLICATIONS OF OHM'S LAW

**Voltmeter-Ammeter Method, or Drop in Potential Method.**—One arrangement of a circuit for measuring resistance is shown in Figure 106. The resistance under measurement is marked $R$, and across, or in shunt with it, is connected a high-resistance voltmeter $V$ to indicate the drop in potential across $R$, and an ammeter $A$ is connected in series with the circuit to measure the current through the resistance. If we assume in this circuit that the current through $R$ is 0.6 ampere and the voltage drop across $R$ is 12 volts then, in accordance with Ohm's Law, we can determine the resistance as follows:

$$R = \frac{E}{I}, \quad \text{or} \quad R = \frac{12}{0.6}, \quad \text{hence} \quad R = 20 \text{ ohms.} \quad \textit{Ans.}$$

**How to Make Up a Test Circuit.**—Figure 107 shows how a 0 to 25 ma. milliammeter and a 0 to 7 volt voltmeter may be connected in a test circuit for the purpose of obtaining a fairly accurate measurement of the value of an unknown resistance.

The readings indicated on the meters, when conducting a test, are inserted in Ohm's Law formula, which is given immediately above the diagram. If you use the regular formula, or $R = E \div I$, you must divide the reading in milliamperes by 1000 to get the value of the current in the unit ampere, and this value is inserted in the formula. If the formula to the right is used the reading in milliamperes can be inserted directly in it and by either method the same result will be obtained.

The 200-ohm rheostat is used to regulate the voltage supplied to the unknown resistance under test and, hence, the rheostat controls the current passing through both the resistance and milliammeter. The current reading should be kept within the limits of the meter by proper adjustment of the rheostat.

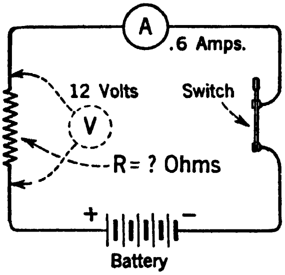


FIG. 106.—A circuit which illustrates the voltmeter-ammeter method (or drop in potential method) for measuring resistance.

$$R = \frac{E}{I} \quad \text{or } R = 1000 \times \frac{\text{Volts}}{\text{Milliamperes}}$$

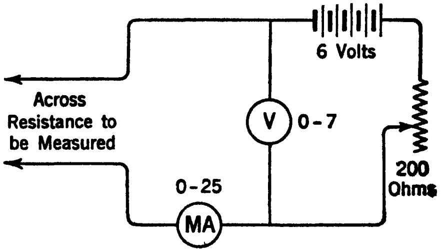


FIG. 107.—A simple test circuit for measuring resistance may be constructed with two meters, a rheostat and a 6-volt battery as shown.

**Wheatstone Bridge.**—In Figure 108 is a very simple form of bridge circuit for accurately measuring resistance values. For this precise method of measuring resistance the principle of voltage drop across two branches of a divided or parallel circuit is utilized. The circuit used in the explanation of this principle is shown in Figure 109, which is a simple form of bridge. The arrangement of the parts can be better understood from the small drawing at the right where the letters on the diagram correspond to those on the larger diagram at the left.

Resistances *A*, *D*, and *B* are called the bridge arms, and each consists of a number of specially wound resistance coils of various values which cover a range sufficient to measure any resistance for which the bridge is designed. Each resistance coil can be cut in or out of its respective arm by removing or inserting metallic plugs in holes which are suitably mounted on the bridge. That is, resistance is inserted in the circuit by removing a plug, and resistance is taken out of the circuit by the short-circuiting of a coil when a plug is inserted in a hole. The unknown resistance to be measured is connected to the terminals of arm *C* as shown.

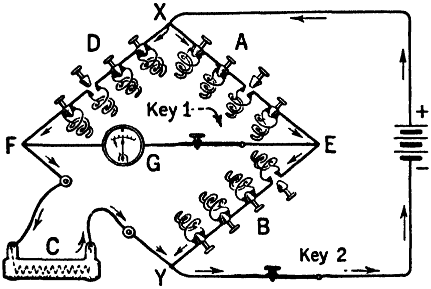


FIG. 108.—A form of Wheatstone bridge circuit for measuring resistance values.

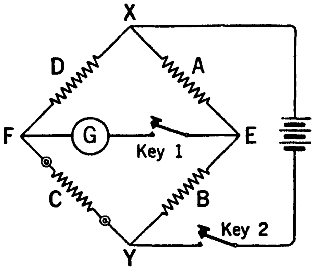


FIG. 109.—The Wheatstone bridge circuit of Fig. 108 reduced to simple schematic form.

The procedure for operating the bridge is to adjust the resistance arms *A* and *D* so that a certain ratio will exist between them, namely, a ratio which will permit a balance to be obtained by varying the resistance of arm *B*. When a balance is found, the galvanometer gives no deflection, and if this result were obtained by making the resistances of *A* and *D* equal then the voltage drop over the *A* branch must equal the drop over the *D* branch, and if these were equal it follows that the drop across the *B* branch must equal the drop across the *C* branch, which means that *B* and *C* also bear the same relation and, therefore, are equal in value. That is, the resistance in *B* equals the resistance of the unknown unit *C* under measurement. When a larger resistance than *B* is to be measured, the arms *A* and *D* should be so adjusted that the ratio of *D* is greater than *A*, and the resistance then required at *B* to get a balance must be multiplied by a number which is obtained by dividing $D$ by $A$. On the contrary, when a smaller resistance than $B$ is to be measured then $D$ is adjusted to a value less than $A$, and this time $B$ must be multiplied by a number obtained in the same way as we have just explained.

The theory of operation of the bridge circuit is as follows: Remember first of all that the operation is based on the fact that the *voltage drop across any resistance is proportional to the value of the resistance and the current flowing through it.* Next remember that when current from the battery flows to point $X$ in our diagram it divides into two parts, one part taking the path through the resistance arms $D$ and $C$, and the other part taking the path through arms $A$ and $B$, after which the two currents come together again at point $Y$ and the total current flows on through key 2, thence through the battery, and so on as described. It must be understood that the current flows as long as the battery supplies the requisite e.m.f. and key 2 remains closed. When the circuit is first placed in operation it is more than likely that the voltage drops across the four ratio arms will be different and, therefore, there will be a difference of potential of a certain amount between points $E$ and $F$, which will cause current to flow in the galvanometer circuit when key 1 is closed with the result that a deflection of the needle will be observed. Suppose now we proceed to adjust the resistances of arms $A$, $D$, and $B$, as outlined above and so proportion them that the voltage drop across $A$ and $D$ will be equal, that is, so that the difference of potential between $X$ and $E$, and $X$ and $F$ will be equal. Then when key 1 is depressed the galvanometer will show no deflection, thus indicating that no current is flowing between points $E$ and $F$ because there is no difference of potential between these points, or across the galvanometer which would send current through its windings. After balancing the bridge in this manner we obtain the values of $A$, $D$ and $B$ and the value of the unknown resistance $C$ is then found by the ratio between the respective arms of the bridge. To express this relation we would say "$C$ is to $B$ as $D$ is to $A$." When this relationship between the four resistances is written in the form of an equation it becomes

$$\frac{C}{B} = \frac{D}{A}$$

Then in order to find the value of the unknown $C$ we have only to substitute the values of the three known resistances $A$, $D$, and $B$ in this equation and solve. For convenience in finding the unknown $C$ we have changed the above formula to the form,

$$C = B \times \frac{D}{A}$$

## PROBLEMS ON CHAPTER VI

**1.** (*a*) If the filaments of five lamps each have a resistance of 20 ohms and they are connected in parallel, what is their combined resistance?

(*b*) How much current will each filament draw if a 4.5-volt battery is connected to them? Draw a diagram.

**2.** Explain why we show the direction of current flow with arrows pointing from positive to negative potential points in our diagram when physicists tell us that the direction of the electron drift through a conductor is from negative to positive.

**3.** Suppose a storage battery supplies three lamps of similar type which are connected in parallel and to these are connected an ammeter and a rheostat in series. If the resistance of each lamp were known to be 30 ohms and the resistance of the rheostat 5 ohms and the ammeter indicated a current of 0.4 ampere what must be the voltage of the battery? Draw a diagram.

**4.** (*a*) Explain why current stops flowing through a circuit when a switch is opened.

(*b*) Why does the current flow when the switch is closed?

**5.** What three important factors must always be considered in the operation of any circuit?

**6.** Suppose a certain circuit consists of two filaments, A and B, connected in series to a 6-volt battery. How much current flows through filament A and through filament B if each one has a resistance of 50 ohms?

**7.** (*a*) Name some of the sources of electric pressure or e.m.f.

(*b*) What does potential drop along a conductor mean?

**8.** Give two definitions of an ampere, one based on chemical action and the other on electronic energy.

**9.** Write Ohm's Law for the following problem and solve, showing all your work: Given a simple circuit consisting of an electric bell having a resistance of 60 ohms which operates at an e.m.f. of 3 volts. Find the current drawn by the windings of the bell whenever it rings.

**10.** Is there any definite relationship between the factors you mentioned in your answer to Question 5? Explain.

## CHAPTER VII

# CONSTRUCTION AND USE OF PRIMARY CELLS

One of the Sources of Electrical Pressure which Is Necessary before Circuits Can be Made to Function Is the Simple Primary Cell. How the Amount of Pressure May be Controlled by Various Groupings of Cells Is Given in This Chapter

The principal *sources of electric power* that are utilized in practically every power and radio installation, including transmitters, receivers, auxiliary equipment, and types of apparatus of unlimited varieties, are the electric *generator* and the electric *battery.* When we say *source of electric power* we mean a *source of electromotive force.* It is customary for some persons to think that a generator or battery stores up electricity and supplies current to any device to which it may be connected, but this is not a fact. A generator or battery merely furnishes an electromotive force (or pressure) which when applied to any device, or circuit, will set electrons in motion and cause them to flow through the device, or circuit. Always keep in mind that the movement of electrons through wires (and all conductors of electricity) is the so-called current flow. Now, since electrons already exist in the wires and other elements that form a circuit, then it cannot be said that a generator or battery supplies them; what the generator or battery does is to *force* these electrons to move through the wires from one place to another, that is, the electrons which constitute the current are forced to flow through a circuit by the e.m.f. (or pressure) applied to the circuit. Thus, it is evident that current will not flow in any circuit unless an e.m.f. is applied to it from some source.

In the case of the *generator* the electromotive force is obtained by making practical use of the laws of *electromagnetic induction.* According to the explanations on this subject in Chapter IV, one law stated that when a coil of wire is moved through a magnetic field an e.m.f. is produced across the terminals of the coil; this is exactly the principle upon which the generator works, since it is constructed to provide a strong magnetic field through which a number of coils are rotated by mechanical means and from these coils we are able to get an e.m.f. or electric power. In the case of the *battery,* however, the e.m.f. is obtained through the *electrochemical action* that occurs between the combination of materials that are used. We learn, therefore, that *a generator transforms mechanical energy into electrical energy and a battery transforms chemical energy into electrical energy.*

Hence, in so far as we are concerned at the present, a generator and a battery produce similar results, that is, either one will provide an e.m.f. Of course, you will understand that many practical and economical considerations determine whether a generator or battery will be used to furnish power for the operation of certain types of equipment. In many of the modern radio broadcast and commercial telegraph installations it has been found necessary to employ both generators and batteries to obtain the best electrical results.

**Classification of Batteries and Cells.**—Let us first explain the distinction between the terms "battery" and "cell." A cell is a complete unit consisting of a chemical solution into which are placed two *different* kinds of materials which are not allowed to touch each other and from which an e.m.f. can be obtained by the chemical action set up between the solution (electrolyte) and the materials. When two or more cells of similar kind are connected together in a combination that permits their individual e.m.f.'s to be utilized all at the same time, the whole combination is known as a "battery." Hence, *a battery is a number of cells* all functioning in conjunction with one another to provide a certain amount of electrical pressure, measured in volts, from its terminal binding posts.

A single cell of the dry-cell type is shown in Figure 110 and its interior construction pictured in the cross-sectional view in Figure 111. This cell has an e.m.f. of approximately 1.5 volts when in good condition. Several cells may be connected to form a battery as follows: Suppose we have three cells of this type connected together to form a battery, then the total e.m.f. at the terminals would be 3 × 1.5 or 4.5 volts. Again, suppose we had thirty cells of this kind connected to form a battery, then the total e.m.f. available at the battery terminals would in this case be 30 × 1.5 or 45 volts. In many dry batteries there are connections taken from different cells in order to provide several different voltages from the same battery for convenience.

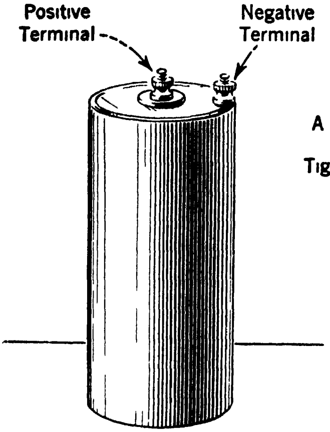


FIG. 110—The standard dry cell.

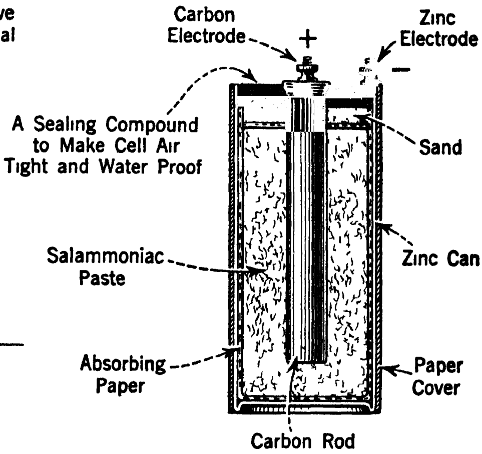


FIG 111—A cut-a-way view of a standard dry cell.

A battery consisting of three small dry cells connected together in series is shown in Figure 112. Notice that terminals are provided so that different voltages may be obtained. A dry battery containing thirty small cells compactly arranged in a container is shown in Figure 113; the e.m.f. at the outside two terminals is 45 volts. In this battery a tap taken between the fifteenth and sixteenth cells is brought to the center terminal on the top so that one-half of the total voltage, or 22½ volts, is available either between the first and second terminals, or between the second and third terminals.

The dry cell and batteries illustrated are typical of the kind found in widespread use for radio and electrical work. A battery similar to the one in Figure 112 is used generally for a specific purpose in radio circuits to supply a negative voltage to the grids of vacuum tubes and it is, therefore, known as a *"C" battery.* The battery in Figure 113 is exactly the same as the one just mentioned so far as its principles of construction are concerned, except that it has more cells than the one in Figure 112. The larger battery in Figure 113 is employed principally to furnish the plate voltage to operate vacuum tubes in certain types of equipment and, consequently, it is known as a *"B" battery.* If several cells of the type in Figure 110 are used to furnish an e.m.f. to the filaments of vacuum tubes in receiving sets, to provide the heating current, the cells are then referred to as an *"A" battery.* It should now be clear that the terms cell and battery are not to be used interchangeably and, therefore, in your conversation and writing be careful to make the correct distinction between them. Say "cell" when you mean cell and "battery" when you mean battery.

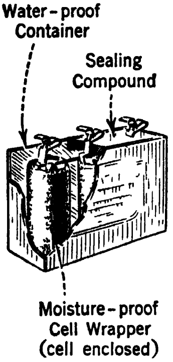


FIG. 112.—A battery consisting of three dry cells; usually referred to as a "C" battery.

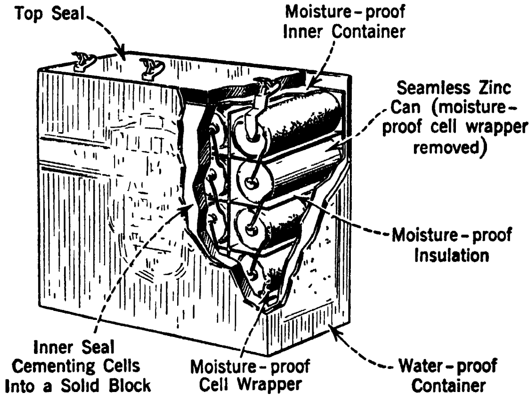

Top Seal
Moisture-proof Inner Container
Seamless Zinc Can (moisture-proof cell wrapper removed)
Moisture-proof Insulation
Inner Seal Cementing Cells Into a Solid Block
Moisture-proof Cell Wrapper
Water-proof Container

FIG. 113.—A battery consisting of thirty dry cells; generally known as a "B" battery. (Courtesy Burgess Battery Company).

**Distinction between Primary and Secondary Cells.**—There are two types of cells in general use; namely, dry cells and storage cells. A dry cell is one that depends for its operation upon the consumption of one of the materials by the chemical action of the solution on it when current flows through the cell and through the circuit to which it is connected. While current flows the *material is gradually eaten* up and in due time it will be entirely consumed, and as a result of this action the voltage (or e.m.f.) of the cell will drop so low that the cell becomes useless for all practical purposes. When this happens the cell must be discarded and replaced by a new one. A storage cell, on the other hand, is one that must first be charged by passing a current through it in a certain direction so that its materials will be put into the proper condition that will enable them to produce an electrical pressure. After the storage cell has been on circuit and delivers a certain amount of current in a stated time, its e.m.f. will fall below the proper working value because the *chemical relations of the cell are then altered.* Since the materials merely undergo a change and are not eaten away, as in a dry cell, it is only necessary to pass current again through the storage cell to restore the materials to their original condition. With intelligent care a storage cell will last for years since it requires only charging and the adding of water at periodic intervals to maintain it in a proper condition. The life of a dry cell, on the other hand, is a more or less fixed condition because it is governed by the rate at which the active material, zinc for instance, is consumed, and this in turn depends upon the amount of electrical energy delivered by the cell. For the reasons just advanced a *dry cell is called a primary cell* and a *storage cell is called a secondary cell.* Primary cells are also known as galvanic cells.

Another important thing to mention is that a dry cell is not really dry as the name would lead almost anyone to believe. The use of the word "dry" no doubt became popular owing to the fact that all of the materials in the cell are sealed up in a moisture-proof container without any outside evidence of a liquid solution in it like in a "wet" battery, for example. During the manufacture of a dry cell a certain amount of water is added to the materials and the liquid is therefore retained in the moist pasty filling which we could see if we broke open a cell.

**Why an Electromotive Force Is Produced by a Dry Cell.—It is a known fact that there is always an e.m.f. of a certain number**

of volts set up between any two pieces of metal of *dissimilar kind* when immersed in a liquid. When certain combinations of materials are used, and the liquid is a chemical solution of a particular kind, e.m.f.'s as high as 2 volts and more can be obtained. The metal pieces referred to are called the "plates" and the chemical solution the "electrolyte." The e.m.f. or voltage of a cell is determined solely by the kind of materials used for the plates and the nature of the electrolyte. The theory is that the electrolyte acts more readily on one material than the other, and it is this chemical action that causes both plates to possess an electric potential, but because of their difference in character one plate will have a higher potential than the other. The higher potential plate is called the *positive plate* and the lower potential plate is the *negative plate.* The difference of potential is *electrical pressure,* and it is capable of sending current through a circuit. The size of the plates, their actual surface area in contact with the electrolyte, or the amount of separation between plates has no bearing whatsoever on the voltage of the cell. However, these factors do have some effect on the internal resistance of the cell, and this in turn will govern to some extent the amount of current that the cell will be capable of delivering.

Hence, if we have one very large cell and one very small cell and each one is made up of a similar combination of materials and electrolyte it will be found that the voltage reading taken between the plates will be alike for the two cells. This would prove our statement that only the materials and the electrolyte govern the e.m.f. or voltage across the plates. A cell consisting of a zinc plate and a copper plate immersed in a liquid of dilute sulphuric acid gives an e.m.f. of approximately 1 volt, regardless of the size of the elements (elements means the materials). Another cell, however, having a different combination of materials, for instance, zinc for one plate, carbon for the other, and a sal ammoniac electrolyte, sets up an e.m.f. of approximately 1.5 volts between its plates.

**Polarization.**—To explain this term let us consider that we have a cell consisting of a zinc plate and a carbon plate being acted upon by a sal ammoniac electrolyte solution. When a cell of this type is connected in a circuit and current flows, the zinc is slowly dissolved, or eaten up, by the chemical action of the sal ammoniac (ammonium chloride). It is the combining of the electrolyte chemically with the zinc and the intensity of the action for this particular set of materials that makes the cell capable of developing an e.m.f. between its plates and, also, of furnishing a given amount of current to a circuit for a given time.

While the chemical action goes on and current flows through the cell a quantity of fine bubbles of hydrogen gas are liberated which immediately gather around the carbon. The bubbles collect very rapidly if the cell passes a current of high value continuously for any length of time, and their presence on the positive carbon plate causes a very noticeable reduction in the current strength. Thus, we see that the hydrogen gas has a detrimental effect on the amount of electrical energy supplied by the cell. This weakening of the cell is called *polarization* and if allowed to continue the cell will cease functioning entirely.

The falling off of the current caused by the hydrogen gas is due to two conditions set up within the cell; first, the gas being a non-conductor of electricity acts as an insulator and increases the internal resistance of the cell and, therefore, actually tends to block the flow of current; secondly, the gas layer on the carbon reduces the amount of active surface material that the carbon can present to the electrolyte, that is to say, the gas acts to separate the carbon from the electrolyte. Moreover, if a cell of this kind is strongly polarized it sets up a small opposition e.m.f. because the character of the plates is altered inasmuch as the carbon plate virtually becomes a hydrogen plate. As far as the chemical action of the cell is concerned it will behave as though it had zinc and hydrogen plates and not zinc and carbon. It has been mentioned before that different combinations of the materials of which a cell is composed will cause the e.m.f. produced between its plates to change also, hence, the e.m.f. of the cell is considerably lowered by the polarized condition.

Polarization is prevented, in a cell when it is operated to give an intermittent current of average value for the particular type of cell in question. In the type already under consideration a strong oxidizing substance, such as manganese dioxide, is used for this purpose as it combines readily with the hydrogen and, therefore, removes the gas from around the carbon. It is to be understood that if an excessively large current is delivered steadily by the cell the chemical action between the oxidizing material and the hydrogen may be too slow to prevent polarization and the cell will become inactive in a short time. However, if a cell when in this condition is disconnected from the circuit and permitted to remain on open circuit for a brief interval, it will rapidly *recuperate*, or recover, which means that it will be restored to normal by the cleaning up of the hydrogen by the depolarizing agent. The carbon then is once more left free to act as a plate and conductor for the passage of current.

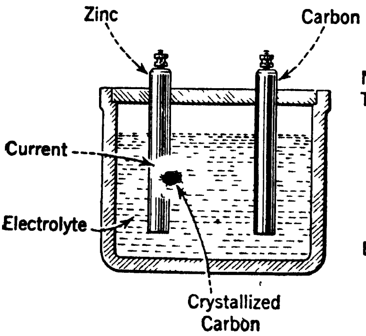


Fig. 114.—Showing the effect of "local action" in a wet cell.

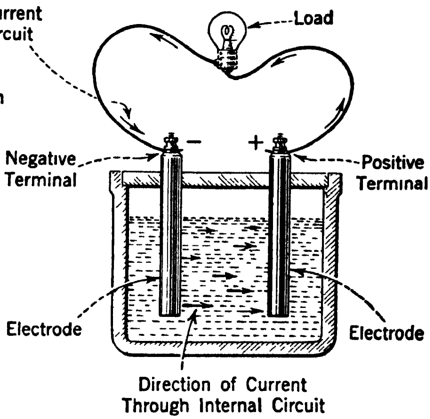

Direction of Current in External Circuit
Load
Negative Terminal
−
+
Positive Terminal
Electrode
Electrode
Direction of Current Through Internal Circuit

Fig. 115.—Here is shown the direction of current flow within a cell (internal circuit) and the direction in the external circuit.

Have you ever noticed when using a pocket flash-light that the light suddenly became dim, but after allowing the switch to remain in the " off " position for a half minute or so the lamp when next lighted would glow with its former brightness? This dimming of the light was caused by the falling off of the current through the cell because of polarization. The same weakening effect is often noticed in the ringing of a door-bell, or in the operation of a buzzer, especially when it is operated *steadily* for a time.

**Local Action.**—If a cell like the one pictured in Figure 114 is left on open circuit (which means that there is no conductor of electricity connected to its respective plates) there should be no chemical action occurring between the materials composing the cell. If the zinc plate is absolutely pure (i.e., without foreign matter or impurities) an internal action cannot be set up and current cannot be produced by the cell's own materials. However, ordinary commercial zinc contains many foreign particles, such as carbon, tin, iron, and so on, and these small foreign particles act with the zinc to set up tiny electrical currents that flow in a short-circuit path as shown in Figure 114. This *local action* causes the zinc to be eaten away continuously, and in time it will affect the normal output energy of the cell. To prevent this consumption of the zinc when the cell is not used to operate a circuit it is customary to rub a small quantity of mercury into the surface of the zinc. This process is called *amalgamation.* Amalgamation, therefore, stops local action when a cell is left on open circuit because the mercury does not combine with the carbon, or other foreign particles, but it does act chemically with the zinc to form zinc-mercury amalgam that works its way over the zinc plates and covers up the particles.

**Action of a Simple Primary Cell.**—Suppose the simple cell in Figure 115 is composed of a positive copper (Cu) electrode, a negative zinc (Zn) electrode, and diluted sulphuric acid. In this combination of materials the acid unites more readily with the zinc than with the copper. The chemical symbol for sulphuric acid is $H_2SO_4$, which denotes that a molecule of this liquid consists of 2 *atoms of hydrogen*, 1 *atom of sulphur*, and 4 *atoms of oxygen.*

The action is explained according to the " electron theory." The important thing to bear in mind is that atoms consist of an aggregation of electrons, and if some of these electrons can be set free by chemical means the free electrons will move through the conductors forming the external circuit around the cell. As we have just stated, the movement of current through the load circuit connected to the cell is simply a movement of electrons. Their direction of flow in the external circuit connected to a cell is from the negative terminal to the positive terminal of the cell. This is in accordance with the theory as explained in Chapter II on

"Static Electricity." It was stated that at a positively charged electrode there is a deficiency of electrons, and at a negatively charged electrode there is a surplus of electrons.

We will attempt to make the following explanation as easy to understand as possible. When chemical action sets up in the cell each molecule of sulphuric acid separates into two oppositely charged parts: namely, *positive ions* which are the $H_2$ or hydrogen part of the acid, and *negative ions* which are the $SO_4$ or sulphuric part of the acid. The negative ions are made up of a certain number of *negative electrons.* Also, a portion of the zinc separates into electrons and positive ions with the latter uniting with the negative sulphate ions, the $SO_4$ mentioned above. But the electrons just made available by the zinc do not unite with other parts and, therefore, they move through the circuit. The repulsive force which electrons exert upon one another (this is because all electrons possess a negative charge of equal amount and have similar characteristics otherwise) causes them to move through the zinc electrode, and through the conductors forming the external circuit, and thence through the copper electrode, and the action just described continues so long as the cell is connected to the external circuit and the materials used in the cell are in good condition. (The external circuit consists of the connecting leads and the load as indicated by the resistance symbol.) The fact that each one of the two parts of the electrolyte goes to an opposite plate when it separates as stated above (that is, the $H_2$ positive ions go to the copper plate and the $SO_4$ negative charges go to the zinc plate) causes the respective plates to become charged electrically to positive and negative potentials. This results in the setting up of a difference of potential between the plates, or terminals, of the cell and the movement of the electrons through the external circuit in the direction from negative to positive.

The arrows in the drawing in Figure 115 are not to be associated with the movement of the electrons in the explanation just given. The arrows merely indicate the direction of *current flow* according to the usual convention or custom in practical use for many years. Note that the *current arrows* are in a direction in the external circuit from the positive terminal to the negative terminal and in the internal circuit from the negative terminal to the positive terminal.

**Construction and Operation of the Common Dry Cell.**—The interior view of a typical dry cell is plainly marked in Figure 111 to identify all of the parts that enter into its construction. Dry cells of this type are usually 6 inches high and 2½ inches in diameter. The zinc cylindrical can is the negative electrode. The terms "electrode" and "plate" are used interchangeably. The zinc can holds the moist black paste in which is embedded a large carbon rod that forms the positive electrode, or plate. The paste usually consists of a mixture of ammonium chloride (or sal ammoniac, the chemical symbol of which is $NH_4Cl$), plaster of Paris, powdered coke, a small quantity of graphite, zinc chloride ($ZnCl_2$), and a depolarizing agent, such as manganese dioxide ($MnO_2$). Enough water is added to the electrolyte to moisten the absorbing paper which lines the zinc can and separates the zinc from the paste. After the paste and carbon rod are firmly packed in, the whole assembly is covered with sand, and on top of this is placed a sealing compound to make the cell moisture proof and thus prevent evaporation.

The great advantage of this type of cell is that it can remain on open circuit for long periods without appreciably shortening its useful life. After a period of a year, or more, it will begin to deteriorate rapidly, if unused. and the drying out of the cell will be hastened if it is kept in a very warm atmosphere. It is always best to keep a dry cell in a cool place whenever possible where the temperature is not much higher than 70° F.

A dry cell is a very convenient means for obtaining an e.m.f., but it is adapted only for use on intermittent work, such as ringing door-bells, telephone installations, or where the service demands only a small continuous current, such as for supplying current to heat the filaments of small receiving type vacuum tubes in radio circuits, and other uses too numerous to mention.

Because of its low internal resistance a dry cell in good condition will deliver a current of about 18 to 30 amperes, or more, when measured on momentary short circuit by means of a low-resistance ammeter. Short-circuit tests should not be made often on the same cell, as it places a heavy drain on the active materials. A voltage test can be made by using a good high-grade voltmeter with a low reading scale. The average e.m.f. of all new standard dry cells in good condition is about 1.5 or 1.6 volts. In certain classes of work after a cell has dropped to about 1 volt it is removed from active service and a new one is substituted. Also, if two or more cells are used in conjunction with one another their individual voltages should be measured frequently to ascertain whether they are nearly alike, or whether one cell is considerably lower than the rest, in which event the operation of the circuit would be seriously impaired.

**Leclanché Cell.**—The standard dry cell is practically a Leclanché cell made up in a different form—both employ similar materials in their construction. The Leclanché cell consists of two cylindrically shaped plates, one of zinc and one of carbon placed in a sal ammoniac solution, the carbon plate being corrugated in shape to form a porous cup in which the manganese dioxide and powdered coke are placed. When delivering current the sal ammoniac solution attacks the zinc, and, as in the case of the simple dry cell, bubbles of hydrogen gas are liberated and collect on the surface of the carbon. The gas combines with the manganese dioxide and is removed, thus preventing polarization of the cell. A cell of this kind will keep in good working condition for years and practically the only attention it needs is an occasional filling with water and sometimes with a fresh supply of sal ammoniac.

### METHODS OF CONNECTING CELLS

A top, or plan view, of a common dry cell is shown in Figure 116. The center terminal connects to the carbon rod, and this terminal is called the "positive pole" of the cell; the (+) sign is used to denote positive polarity. We do not as a rule call this a "plus" sign in this work; we generally say "positive" sign. The terminal at the outer edge of the cell connects to the zinc can, or shell, of the cell and this terminal is called the "negative pole"; the sign (−) is used to denote negative polarity. We do not call this a "minus" sign as a rule but rather a "negative" sign. Hence, we say that a dry cell has *two terminals, one a positive* and *the other a negative.*

The small sketch in Figure 117 is one way of drawing the top view of a cell and indicating the amount of e.m.f. in volts at which the cell is rated or, in this case, the cell is seen to have a "terminal" e.m.f. of 1.5 volts. Instead of drawing a picture of a dry cell each time we desire to indicate one on a diagram we make use of the standard symbol as shown later on in this chapter. The long thin line represents the positive pole, whereas the short heavy line represents the negative pole.

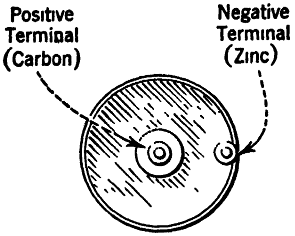


Fig. 116.—A pictorial view of the top of a standard dry cell.

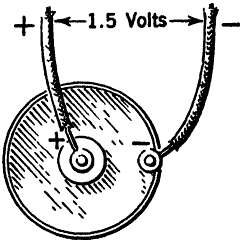


Fig 117.—A standard dry cell delivers approximately 1.5 volts across its terminals when new.

There are two ways in which the cells of a battery may be arranged to vary the current output of the cells: (1) by a *series* combination; and (2) by a *parallel* combination.

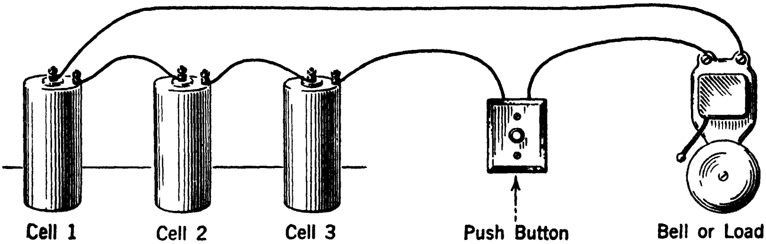


Fig 118.—A circuit in which three dry cells are connected in series.

(1) By the *series* method the e.m.f. of the battery is increased because the single cells are connected in a way that permits the *sum* of all of their e.m.f.'s to be available. When cells are joined in series the total resistance of the combination is equal to the sum of the internal resistances of the individual cells. In Figure 118 three cells are shown joined in *series* and connected to a bell and push button.

(2) By the *parallel* method the e.m.f. of the battery will not be greater than that of a single cell, but the total resistance of the battery decreases with each addition in the number of cells used. Refer to Figure 119, showing three cells joined in *parallel* and the combination connected to a bell and controlled by a push button.

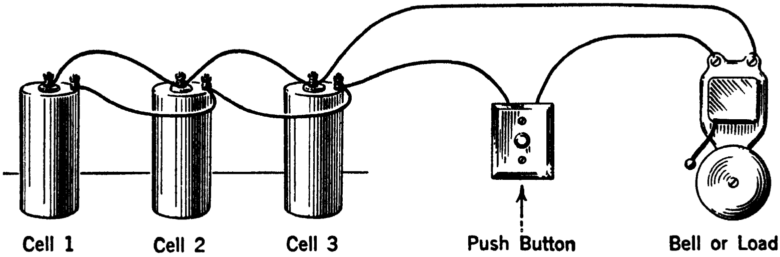


Fig. 119.—A circuit in which three dry cells are connected in parallel.

**Series Combination.**—Both Figures 118 and 119 are pictorial diagrams drawn to assist you in understanding just how the cells are actually connected. Notice that in the series combination in Figure 118 the connecting wires are put on according to the following system: The negative terminal post of cell 1 is joined to the

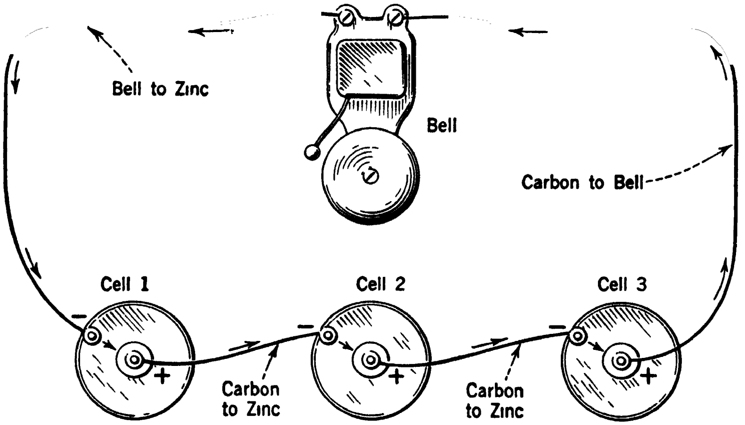


Fig. 120.—A picture method of illustrating how cells are connected in series.

positive of cell 2; the negative of cell 2 is joined to the positive of cell 3; the negative of cell 3 is joined to one terminal on the push button; the other push button terminal is joined to one terminal on the bell; the other terminal on the bell is connected to the positive terminal of cell 1. Thus, we have made a complete circuit, beginning at cell 1 and returning to it. In this arrangement the same amount of current that flows through one part of the circuit must also pass through all other parts, since there is only one continuous circuit formed. Now refer to the diagram in Figure 120, which illustrates the top plan view of the cells in Figure 118 in slightly different form. The purpose of Figure 120 is to show that when we connect two cells from positive to negative we are in reality connecting the carbon of one cell to the zinc of the adjoining cell. It is a simple matter to trace out the "continuity" of this circuit by means of the wiring which is plainly marked. The word "continuity" expresses just what we are doing, that is tracing out a circuit from beginning to end to see that it is continuous and unbroken, so that we may be sure that current will flow through all its parts. The course of the current is shown by the arrows.

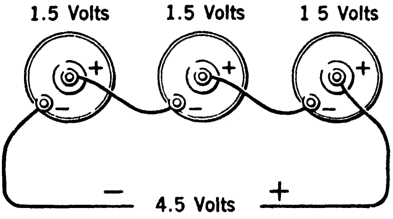


FIG. 121.—A pictorial drawing to show the additive effect of the voltage of dry cells when connected in series.

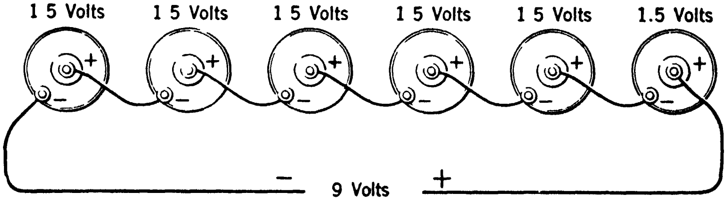


FIG. 122—Six dry cells are connected in series arrangement to provide increased voltage

Now let us study the drawing in Figure 121, showing three cells joined in series. If each cell has an e.m.f. of 1.5 volts the sum of the e.m.f.'s will determine the amount of voltage available at the output terminals, or in this case, 3 × 1.5 equals 4.5 volts, as marked on the drawing. This time consider the group of cells joined in series in Figure 122. The voltage supplied to any circuit connected to the two outside terminals of these cells would be 6 × 1.5, or 9 volts.

Figure 123 illustrates series groupings of cells similar to those already given but they are drawn in slightly different form. The single cell at the left is shown to point out the relation between a cell and its symbol. We have arranged these diagrams in slightly different form, so that you will become accustomed at the very start of your work to read a schematic diagram drawn in any manner.

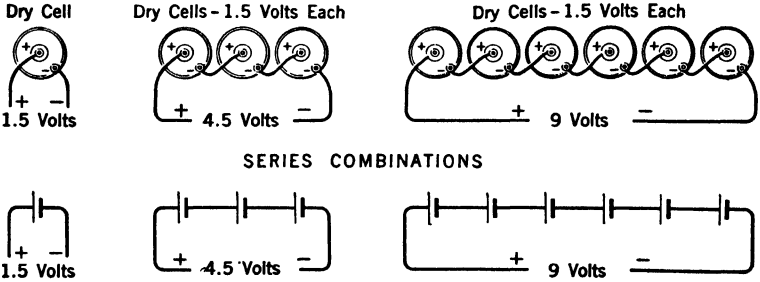


FIG. 123.—Pictorial and schematic diagrams of dry cells connected in series to show how different voltages may be obtained.

EXAMPLE: Suppose we have a battery consisting of 12 cells, each rated at 1.5 volts, with the cells in series. What is the total voltage available? The answer is 12 × 1.5, or 18 volts.

EXAMPLE: If the internal resistance of each of the cells in a group of 12 connected in series is 0.5 ohm, what is the total internal resistance of the cells? The answer is 12 × 0.5 ohm, or 6 ohms.

From the foregoing explanations we learn that to find the resultant voltage, or e.m.f., of any number of cells connected in a series combination, it is only necessary to multiply the voltage of any one of the cells, providing they are all alike, by the number of cells in the group. Also, to find the internal resistance of all of the cells taken together in a series combination we must multiply the internal resistance of one of the cells, providing they are all alike, by the number connected in the group.

The drawing in Figure 124 shows two pumps connected together in such a way as to make it easy to visualize how the total pressure at the outlet pipe at the extreme right is the sum of the individual pressures of each pump when in operation. In this case the quantity of water flowing through the outlet pipe at the extreme right is no greater than that which enters the inlet pipe at the extreme left of the first pump, but the higher pressure is useful in forcing the water available through a line which may offer considerable opposition. We have a similar condition in an electric circuit when cells are connected in series; the voltage of every cell in the battery contributes its pressure additively, and since a larger voltage is available a stronger current can be forced through a given circuit to perform a certain amount of electrical work.

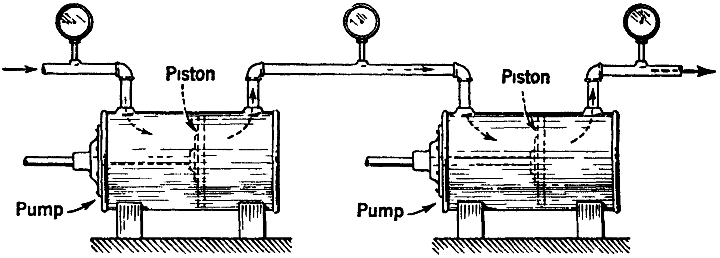


FIG. 124.—A water analogy which aids in explaining the effect of connecting cells in series

**Parallel Combination.**—Figure 125 is a picture diagram of a parallel or multiple grouping of cells where the e.m.f. or voltage of the whole combination is only the e.m.f. of a single cell. The drawing shows that all the negative terminals (−) are connected together and, therefore, we have but one lead coming from the negative side of the cells that is common to all negatives. All the positive terminals (+) are also connected together, which provides only one common lead coming from the positive side of the cells. Observe that the connecting wires are put on according to the following system: The zinc of cell 1 is joined to the zinc of cell 2;

the zinc of cell 2 is joined to the zinc of cell 3 and, from this point, a lead is carried to the bell. Next we have the carbon of cell 1 joined to the carbon of cell 2; the carbon of cell 2 joined to the carbon of cell 3; and then a connection is carried from this point to the other terminal on the bell. Thus we have completed the *continuity* of this parallel arrangement of cells. The path of the currents furnished by the individual cells and the total current flowing to the bell are represented by the arrows.

In this arrangement the internal resistance of the battery is reduced if cells are added to the group. For example, the internal resistance of the three cells in the battery in Figure 125 is one-third that of any single cell. If there are two cells in a parallel grouping, as in Figure 126, the internal resistance is one-half that of either cell. When speaking of changing the internal resistance of cells by various groupings we do not mean that the resistance within any of the cells is changed, but the effect on the electrical circuit comprising the cells is like that of any grouping of resistances, that is, if several resistances are connected in series the total effect is to increase the resistance, whereas if the resistances are in parallel the total effect is to reduce the resistance.

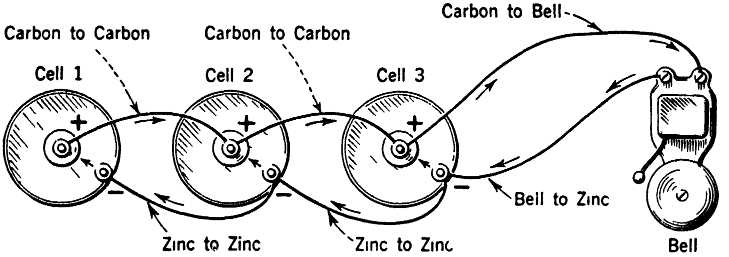


FIG. 125.—This grouping of three cells connects them in parallel, or multiple, to a load circuit, the bell.

We learned in the first part of this chapter that the amount of zinc exposed to the action of the electrolyte determined the amount of current that would be delivered by the cell and that the voltage of all standard cells are exactly alike, regardless of their size, when the same combinations of materials are employed. Hence, in a parallel grouping of cells we have the effect of increasing the area of the plates, since the zincs of all the cells are connected together; but we do not obtain an increase in the e.m.f. according to the consideration that certain combinations of materials give a known e.m.f., and the size, or area, of the materials has no influence on this voltage. The advantage of connecting cells in parallel is that each cell contributes an equal amount of the current delivered by them.

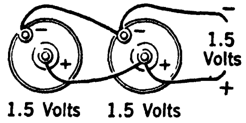


Fig. 126.—Two cells in parallel.

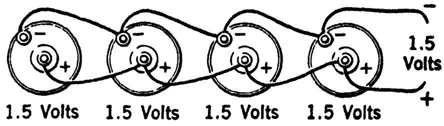


Fig. 127.—Showing four dry cells connected in parallel.

Hence, suppose the battery in Figure 127 consisting of four cells in parallel is connected to a circuit which is passing 2 amperes, then each cell of this group would contribute one-fourth of 2 amperes, or 0.5 ampere to the circuit. Thus, the load would be divided equally among the cells. If all the cells were forced to pass 2 amperes through them to supply such a cricuit the cells would deteriorate very rapidly. In Figure 125 suppose the actual current passing through the bell is 0.15 ampere; each cell then would furnish one-third of this amount, or 0.15 ÷ 3 equals 0.05 ampere.

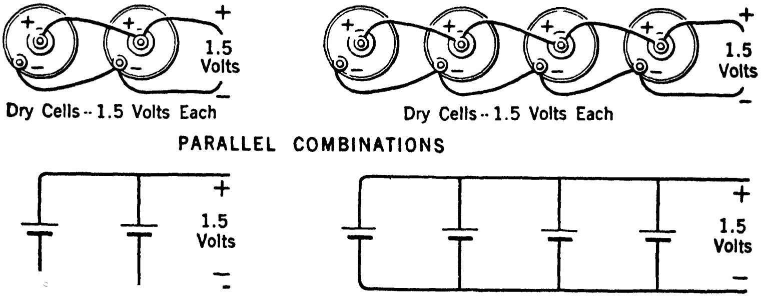


Fig. 128.—Pictorial and schematic diagrams of dry cells connected in parallel.

Figure 128 shows two parallel combinations of cells. The e.m.f. of the left-hand battery is 1.5 volts, which is the e.m.f. of any one of the cells; and the e.m.f. of the right-hand battery is also 1.5 volts, which is likewise the e.m.f. of any cell in the group.

The water analogy in Figure 129 gives a clear idea of the effect of connecting cells in parallel where the pressures are not added up but each cell merely contributes its share or *quantity* of current to the circuit to which it is connected.

Note that the two pumps in Figure 129 are connected in such a manner that their individual pressures do not add to increase the pressure in the water line at the outlet at the extreme right; in other words, the pressure at the outlet is not greater than either of the pumps. What happens is the total volume of water passing through the outlet pipe is equal to the water supplied by both pumps.

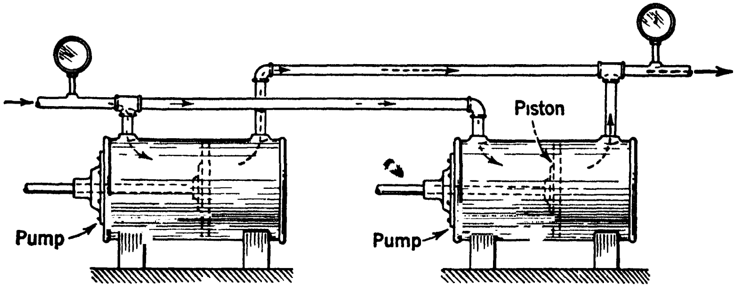


Fig. 129.—A water analogy which aids in explaining the effect of connecting cells in parallel

**Parallel-Series Combination.**—The schematic diagram in Figure 130 shows nine cells connected in a parallel-series arrangement. In this circuit we have three separate series groups each of which consists of three cells connected in series, and the three series groups are joined in parallel. By reading the diagram we see that a parallel-series combination is a parallel connection of a number of series-arranged cells.

The e.m.f. across each series connection is 4.5 volts. In a parallel combination of cells the e.m.f. is the same across the component parts, hence the e.m.f. across the three groupings is 4.5 volts and this is applied to the load circuit, as marked on the diagram.

**Series-Parallel Combination.**—The circuit illustrated in Figure 131 consists of twelve cells connected in a series-parallel arrangement. Observe that there are three separate parallel groups each of which consists of four cells connected in parallel, and the three parallel groups are joined in series. Hence, a series-parallel combination is a series connection of a number of parallel-arranged cells.

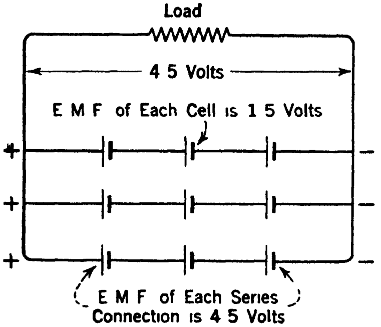

Load
4 5 Volts
E M F of Each Cell is 1 5 Volts
+
+
+
-
-
-
E M F of Each Series Connection is 4 5 Volts

FIG. 130.—A parallel-series grouping of cells.

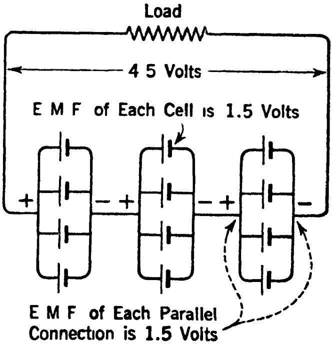

Load
4 5 Volts
E M F of Each Cell is 1.5 Volts
+
- +
- +
-
E M F of Each Parallel Connection is 1.5 Volts

FIG. 131.—A series-parallel grouping of cells.

The e.m.f. across the battery in Figure 131 is 4.5 volts because the e.m.f. across each parallel group is 1.5 volts, i.e., the total e.m.f. of the three groups in series is their sum, or 4.5 volts, as marked on the diagram.

**Summary.**—The principal facts that should be remembered from this chapter are given in the following summary. In the previous chapter dealing with Ohm's Law the mathematical relation between the resistance, the voltage and the current in a circuit was explained. It is advisable that you practice drawing cells in various combinations so that reading simple schematic diagrams will not be confusing or difficult.

In a primary cell one plate is consumed by the action of the electrolyte when the cell produces an e.m.f.

Polarization is caused by a layer of hydrogen gas bubbles collecting on one of the plates.

Local action is due to impurities and foreign particles such as carbon, iron, etc., in commercial zinc.

## RESULTS OBTAINED FROM VARIOUS CELL COMBINATIONS

### VOLTAGE—RESISTANCE—CURRENT

### Series arrangement of cells.

*Voltage:* The total e.m.f. of a series combination of cells is the sum of the e.m.f.'s of the individual cells.

*Resistance:* The combined resistance of cells in series is increased by adding cells. The total resistance is the sum of the internal resistances of the individual cells.

*Current:* In practice cells are usually connected in series (to increase the e.m.f.) when the resistance of the load circuit (or external circuit) is high in order to obtain the proper current.

### Parallel arrangement of cells.

*Voltage:* The total e.m.f. of a parallel combination of cells is equal only to the e.m.f. of any cell in the group providing they are of similar kind.

*Resistance:* The combined resistance of cells in parallel is decreased by adding cells. The total internal resistance is equal to the internal resistance of one cell divided by the number of cells.

*Current:* In practice cells are generally connected in parallel when the resistance of the load circuit is low so that each cell contributes its share of the total current in the circuit.

## PROBLEMS ON CHAPTER VII

**1.** (*a*) When would you use a series connection of cells?
(*b*) What is the advantage of connecting cells in series?
(*c*) How is the total e.m.f. of a series combination of cells computed?

**2.** (*a*) What is meant by local action?
(*b*) Do you know of any remedy for local action? Explain.

**3.** If you were given 15 dry cells and asked to connect them in a group which would supply a certain circuit with an e.m.f. of 4.5 volts, how would you do it? Answer this question by drawing a schematic diagram using symbols.

**4.** What is a primary cell?

**5.** (*a*) When would you use a parallel grouping of cells?
(*b*) What is the advantage of a parallel connection of cells?
(*c*) How is the total e.m.f. of a parallel combination of cells figured?

**6.** (*a*) What determines the e.m.f. of a dry cell?
(*b*) What determines the useful life of a primary cell?

**7.** Name the materials used in some one type of primary cell.

**8.** What is the difference between a cell and a battery?

**9.** (*a*) What is polarization? (*b*) How may polarization be reduced?

**10.** Can a primary cell be charged and used again like a storage cell? Why?

**11.** (*a*) If a battery consists of 8 dry cells of 1.2 volts each connected in series what is the total e.m.f. available from the battery?
(*b*) If these 8 cells were connected in parallel what would be the total e.m.f. available?
(*c*) If two separate groups of the cells in (*a*) above were made up with each group consisting of 4 cells connected in parallel and the two groups were then connected in series what would be the e.m.f. available?

**12.** (*a*) Is the combined resistance of cells increased or decreased when they are connected in parallel? (*b*) When connected in series?

**13.** If you had 16 cells with an e.m.f. of 1.5 volts each how would you connect them to provide an e.m.f. of 12 volts to operate a given circuit? For your answer draw a schematic diagram using symbols.

**14.** Explain what "voltage drop" means.

**15.** Suppose you had two resistors of 15 ohms each and three resistors of 20 ohms each and they were all connected in series with one another and were supplied with power from two $4\frac{1}{2}$-volt batteries connected in series what would be the voltage drop across each 15-ohm and 20-ohm resistor?

**16.** Find the total resistance of the circuit in Figure 100 with the following values substituted for those given on the diagram. The upper left parallel group 5 and 10 ohms, respectively; the upper right parallel group 40, 60, and 80 ohms, respectively, and the series resistor on the lower leg of the circuit 12 ohms. Now find the total current drawn by the circuit if the e.m.f. is supplied by three 1.4-volt dry cells connected in series.

**17.** In the circuit in Figure 100 what would be the voltage drop across the 20-ohm resistor shown in series with the circuit if the e.m.f. were furnished by 6 dry cells which test 1.3 volts each, and the dry cells were connected in parallel?

# CHAPTER VIII

# SOUND

SOUND IS CONSIDERED AS ONE OF THE PRINCIPAL SUBJECTS IN RADIO SCIENCE. PERSISTENT EFFORTS ARE BEING MADE BY THE ELECTRICAL AND RADIO INDUSTRIES TO IMPROVE THE ELECTRICAL CIRCUITS AND DEVICES WHICH COMPRISE SOUND-REPRODUCING SYSTEMS

**Definition of Sound.**—It is well to have a good understanding of the meaning of *sound* because of its importance in radio. Sound can be considered as a series of vibrations of the air of such frequency and strength as to make it audible to the human ear. The human ear responds to a range of frequencies from about 16 cycles or vibrations per second to frequencies in the neighborhood of 10,000 to 15,000 cycles per second. This range varies with different people and usually becomes more limited as a person grows older owing to the fact that, with age, the membrane in the ear, known as the ear-drum, becomes stiffer and less pliable. This added resistance to the action of the air vibrations upon the ear-drum cuts off the range of hearing at the upper and lower ends of the frequency range so that an older person may not be able to hear sounds lower than about 30 cps or higher than about 2000 cps. (Cps is the abbreviation for cycles per second.)

For explanation of the term " cycle " let us refer to Figure 132, which is a pictorial representation of a simple generator of sound waves or air vibrations. If a light piston several inches in diameter is set in rapid oscillating motion (vibration) by some external means, sound waves are produced because the air in front of the piston is compressed when it is driven forward, and the surrounding air expands to fill up the space left by the retreating piston when it is drawn back. Thus we have a series of *compressions* and *rarefactions* (expansions) of the air as the piston is driven back and forth. Owing to the fact that air is elastic these areas of compression and rarefaction do not remain stationary but move outward in all directions. A cycle may be said to consist of an area of compression and an area of rarefaction which corresponds to one outward and one inward movement of the piston. To make the terms "compression" and "rarefaction" clearer it can be said that an area of compression has more than normal air pressure, whereas an area of rarefaction has less than normal air pressure or is, in effect, a partial vacuum. In Figure 132 the areas of compression are shown by the dark or shaded portions and the areas of rarefaction by the lighter spaces between.

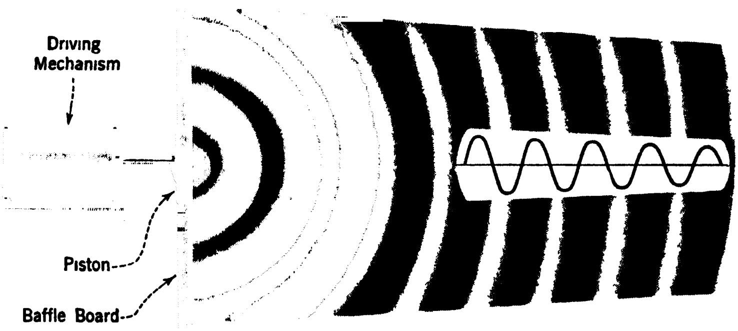


FIG 132.—A means for representing sound waves produced by a moving diaphragm.

The sine wave which is the black wavy line superimposed on the white inset in Figure 132, is a symbol that is used to represent cycles. The high or upper part of each curve shows, in this case, the area of compression, and the lower part of the curve the area of rarefaction. Starting at the horizontal line the sine wave, during the first cycle, rises to a maximum value, then falls past the horizontal line to the lowest part of the curve, returning to the horizontal line on its way up again. At this point it is ready to start the cycle of operations all over again and, therefore, is said to have completed one cycle. In this operation it can be seen that the sound wave traversed a complete area of compression and rarefaction. Inspection will reveal that there are 4½ cycles represented in this "train" of sine waves. It follows that it represents also

$4\frac{1}{2}$ cycles of sound waves. If the impulses imparted to the air by the piston strike upon the ear the ear-drum responds and the brain receives the sensation of sound, provided, however, that these impulses are in the range of audibility. There is another condition which determines whether or not the ear-drum will respond to impulses striking upon it and that is the force of the impulses or, as it is more familiarly known in sound study, the *amplitude*.

In Figure 132 the areas of compression are heaviest nearest the piston, which is the source of disturbance, and lighter in degree as the distance from the source increases, until we can imagine that after a time it would be difficult to distinguish between the area of compression and the area of rarefaction. So it is with the ear-drum in relation to the actual areas of compression and rarefaction which strike upon it. If the *amplitude* of sound waves is great enough (in other words, if the difference between areas of compression and areas of rarefaction is such that it causes the ear-drum to move in and out; "in" as the compression half of the cycle strikes it and "out" as the rarefied part of the cycle arrives) the effect of *hearing* will register on the brain.

In Figure 132 the height of the sine wave train is shown as constantly diminishing, which denotes decreasing amplitude or a gradual decrease in the strength of the disturbance. The piston principle is used in reproducing sound, because it is similar to the action of the diaphragm in a head-phone or loudspeaker, where the diaphragm has a motion backward and forward, either as a whole or when only its central portion moves. However, sound is produced when air is set into vibration by any means whatever, provided that the frequency (number of vibrations per second) is such that it is in the range of audibility.

In many instances sound is produced by some vibrating object which is in contact with the air. For example, if we take a string, such as is used on a banjo or similar instrument, stretch it taut between two solid supports and pluck it, sound is produced which dies out in a comparatively short time. When the string is plucked it tends to spring back into its original position but, owing to its weight and speed, it continues beyond its normal position, oscillates back and forth through its normal position and gradually comes to rest. Figure 133 shows this action pictorially.

As the string moves forward it pushes the air ahead and, hence, the air becomes compressed; also air rushes in to fill the space left behind the moving string. As the string returns to normal, and continues beyond, it creates an area of rarefaction. In this way the air is set into vibration. Since air is an elastic medium, the portion disturbed in turn transmits its motion to the surrounding air so that the disturbance or sound waves are propagated in all directions from the source. Now suppose one end of the string is connected in some way to the center of a diaphragm, such as the stretched drum-head of a banjo, and the string were plucked, then its motion would be transmitted to the drum-head. Because of the fact that a drum-head has a large area exposed to the air a greater volume of air would be set in motion and a much louder sound produced than in the case when the string vibrates alone, as in Figure 133.

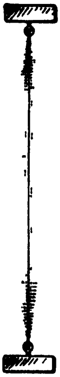


FIG. 133.—When a fairly taut string is plucked it will vibrate back and forth until it comes to rest.

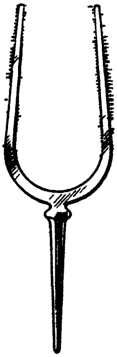


FIG. 134.—A tuning-fork will vibrate at its natural period when it is struck.

Every object has a natural period of vibration which is dependent on its size, shape, weight and material. For instance, a short pendulum has a shorter period of vibration (or swing) than a long pendulum. The movement of a pendulum from a vertical position upward to the extreme left of its swing, then down through its vertical position and up to the extreme right of its swing, and back to its vertical position, is equivalent to a cycle of its motion, or a complete period of vibration. In this case we are able to see the vibration, so by counting the number of swings per second we have the frequency of its vibration. Most objects which we cause to vibrate to produce sound have frequencies which are too high to be counted by any such simple means as this; nevertheless they do have fixed natural periods of vibration which can be determined by finer methods.

A well-known example of a fixed natural period of vibration is the tuning-fork, shown in Figure 134. It is made of tempered steel and is of such size, shape and weight that when struck and set into vibration it vibrates at a constant frequency and produces a musical tone corresponding to that frequency. Thus it can be used in tuning other instruments because it can be transported easily without losing its accuracy and can be depended upon to produce a pure tone of the pitch for which it was designed. Two tuning-forks of the same pitch or frequency can be used to demonstrate that the condensations and rarefactions that make up a sound wave actually have power to move a body of considerable mass. This is explained by the fact that sound waves consist of successive tiny pushes and pulls (condensations and rarefactions) and thus a piece of metal as large as a tuning-fork could be kept vibrating indefinitely by the effect of one tuning fork on another when the pitch of each is the same.

It now should be apparent that it is an easy matter for these air waves to move the light membrane of the ear-drum at the same frequency as that at which the source vibrates. If one of two tuning-forks of the same frequency is struck and set into vibration the other will start up from a state of rest and vibrate at the same frequency even though the two forks are not connected in any way except by the air between them, as mentioned in the previous paragraph. This is due to the air condensations and rarefactions set up by the first fork beating upon the prongs of the second fork, thus setting them in motion. If the vibrations of the first fork are stopped by placing the hand upon it, the tone of the second fork will still be heard until it dies down through lack of impulses from the first fork. The reason one fork responds to the vibrations of the other is that the natural period of vibration of each fork is the same.

The *pitch* of any tone is due entirely to the number per second or frequency of the vibrations emitted, whereas *loudness* is dependent on amplitude alone. Figure 135 shows the range of certain musical instruments and the human voice. It will be seen that each note, whether produced by any of the musical instruments or the voice, is due to a certain number of vibrations per second ranging from the lowest note on the piano, at 26.667 cps, to the highest note of the organ, at 8192 cps.

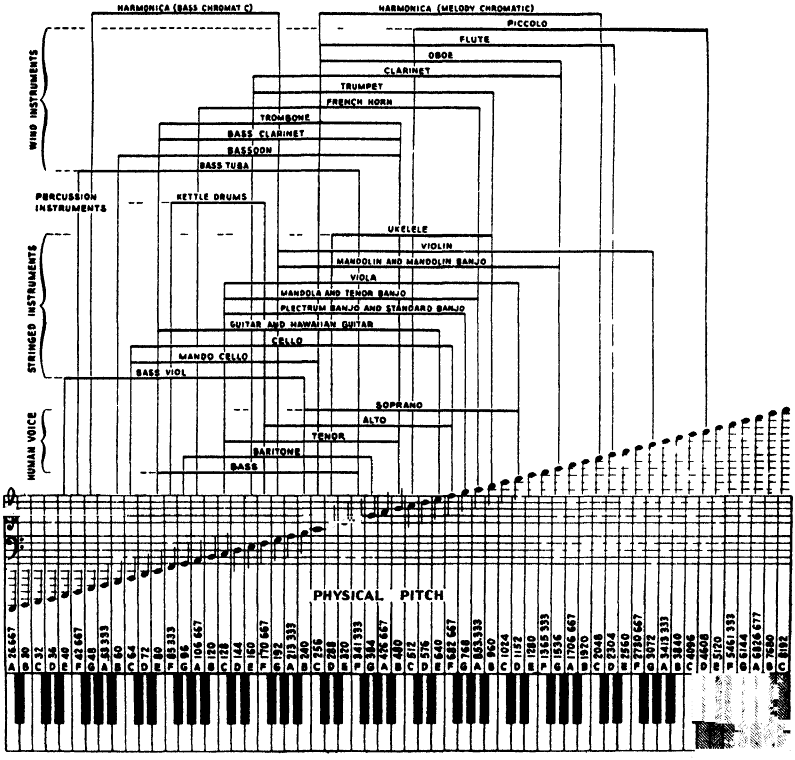


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FIG. 135.—Range of the human voice and certain musical instruments.

One might well inquire at this point why it is that we can distinguish between musical instruments of different kinds when playing the same notes. For instance, referring again to Figure 135, we see that pitch D at 288 cps may be produced by the voice, guitar, banjo, viola, violin, trumpet, clarinet, and other instruments. As previously inferred, no two of these instruments sound the same, and we can distinguish between them even though each may be playing a note of the same pitch. It must be, then, that some other factor enters into the production of the special "quality" of tone that makes each instrument sound different from any other. This "characteristic tone," as it is called, is brought about by the presence of *harmonics* or overtones. Taking the stringed instruments as an example, we find that each string vibrates as a whole, which produces the pitch of the fundamental tone, for instance pitch D would produce a fundamental of 288 cps. A string vibrating as a whole and producing a fundamental tone only is represented in Figure 136.

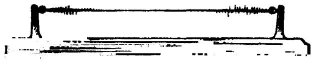


FIG. 136.—When a musical string is plucked it vibrates as a whole which produces the pitch of the fundamental tone.

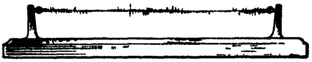


FIG. 137.—A musical string when plucked ordinarily vibrates in section as well as a whole and the smaller vibrations produce harmonics.

Now, as strange as it may seem, it is possible for a string to vibrate in several different modes at the same time ("mode" is another name for "way"). When plucked a string will vibrate as a "whole" as shown in Figure 136 and, at the same time, different sections of the string vibrate at a faster rate than the fundamental or main motion of the string. By combining the fundamental motion as in Figure 136 and the additional movements of the sections as in Figure 137 we obtain the principle why the same notes from different instruments sound quite different as further explained. The tone emitted by the string vibrating as a whole has a certain frequency which is known as the fundamental tone or *first harmonic.* The tone emitted by the string vibrating in two parts has twice the frequency of the fundamental and is called the *second harmonic.* We know from experience that if two different tones are sounded together they blend into a tone that is quite unlike either of the single tones sounded separately. If one is a harmonic of the other the blended tone is usually "richer" in sound. Some instruments owe their richness of tone to strings that have several modes of vibration simultaneously, that is, the strings, besides vibrating as a whole, may vibrate in two, three, four and five parts at the same time, and so on, thus producing first, second, third, fourth, and fifth harmonics. The blending of all these harmonics or overtones into one tone affects the ear agreeably and we hear "richness" of tone. We also come to identify this *characteristic tone* as belonging to a particular type of instrument.

In wind instruments (trombone. clarinet, oboe, flute, piccolo, and so on) the sound is produced by a vibrating column of air the length of which is changed by stopping or opening certain holes (as in the flute and clarinet) or changing the length of the air passage by moving slides (as in the trombone). A column of air will also vibrate in parts as well as a whole, as shown in sketches *A*, *B*, *C*, and *D* in Figure 138. Sketch *A* shows a closed organ pipe with an inlet for compressed air which enters at *a*, passes upward and strikes the sharp lip *b*. The first rush of air produces a condensation which travels up the tube to *c* and is then reflected back to *b*. As this condensation returns it tends to force air out at *b* and therefore deflects the stream of air outward as indicated by the arrow *h*. This action gives rise to vibrations of the air column.

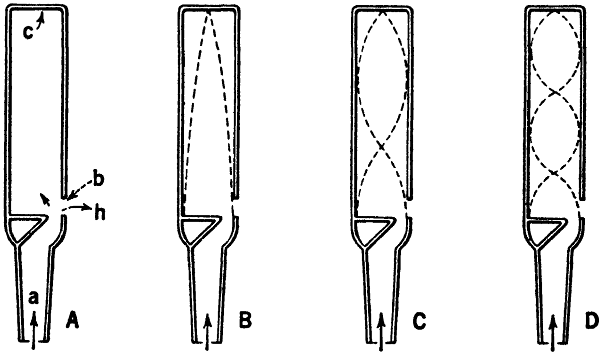


FIG. 138.—An organ pipe is here illustrated to explain that the vibrations of air columns produce musical sounds.

It vibrates as a whole as depicted in sketch *B*, Figure 138, and at the same time in parts as in sketches *C* and *D*. The combination of the fundamental tone (sketch *B*) and its harmonics (sketches *C* and *D*) produces the characteristic tone of the organ pipe which we all recognize instantly.

**Speed of Sound.**—The speed or velocity of sound through air is about 1100 feet per second. It travels through liquids and solids faster than through air, its speed through steel being about fifteen times faster than through air. Sound will travel so much faster through water than through air as to enable you to hear the explosion of a cannon twice if it is fired from a position on the other side of a comparatively small body of water from where you are standing. The sound is first heard as it comes up from the water and later as it comes through the air.

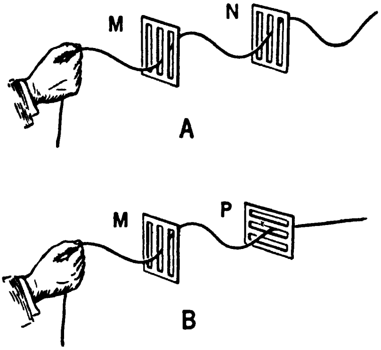


Fig. 139—This analogy shows the motion of sound (longitudinal) waves and light (transverse) waves

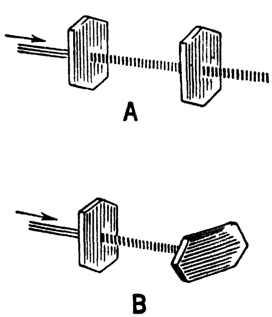


Fig 140—Tourmaline crystals are used here to prove that light waves are transverse in character.

Sound waves are said to be *longitudinal* in character whereas light waves are *transverse* in character. To explain this more clearly let us refer to Figure 139. A transverse wave is one whose motion is perpendicular or at right angles to the direction in which the wave is traveling. A water wave is a good example for a clearer explanation, for, although the disturbance travels out horizontally over the water, the particles of water comprising the disturbance move only in a vertical path the same as the rope in Figure 139. Such a wave in a rope will travel through the two gratings (*M* and *N*) as long as the slits are vertical as shown in sketch *A*, but if one of the gratings is turned so that its slits are horizontal, as shown at *P* in sketch *B*, the wave will pass through one grating but will be stopped by the other.

It can be proven that light waves are transverse in character by the use of two tourmaline crystals as shown in Figure 140. Tourmaline has a crystalline structure comparable to the gratings of Figure 139. As long as the axes of each piece of crystal are kept parallel, light will pass through (see sketch *A* in Figure 140). However, if the axes are crossed the light will be cut off (sketch *B*) as in the case of the motion of the rope wave in sketch *B* of Figure 139. This experiment demonstrates that light waves are transverse in character. A sound wave motion which is longitudinal in character has the effect of moving back and forth in the same plane of direction in which the wave is traveling. If the rope in Figure 139 were to be stretched taut and pulled backward and forward it is easily seen that no matter which way the slits in the gratings were turned the motion of the rope would not be hindered. In other words, by referring to the wavy line in sketch *A*, Figure 141, it will be observed that the transverse or light wave, and the direction of motion of each particle, is in a vertical plane, whereas a longitudinal or sound wave, shown in sketch *B*, is composed of particles of air moving backward and forward in a horizontal plane as depicted by the arrows.

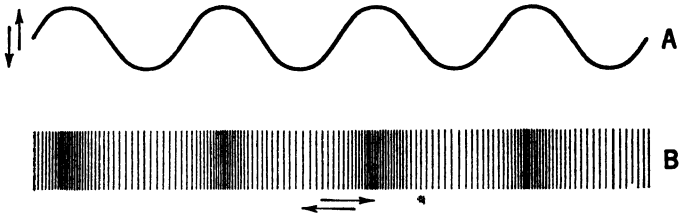


FIG. 141.—Showing in curve *A* that a light (transverse) wave moves in a vertical plane, and in *B* that a sound (longitudinal) wave moves in a horizontal plane.

**Wavelength, Velocity and Frequency.**—The length of any type of wave is the distance from the beginning of one cycle to the beginning of the next cycle, or the distance between any two points taken at similar locations on two successive cycles. In Figure 142 a wavelength, which is also a cycle, is from *a* to *b* in each case. Wavelength, velocity (speed), and frequency all have a definite relationship to one another. For instance, if sound travels at a velocity of 1100 feet per second and the frequency (number of waves per second) is 550 cycles, there are 550 waves in the 1100 feet that the sound covers in 1 second. Hence, if we want to know the length of a single wave all we have to do is divide the 1100 feet by the frequency, and in this case 1100 is divided by 550 (the number of waves in it) and we get 2 feet as the answer. By this simple method we find that the wavelength of a sound having a frequency of 550 is 2 feet. If the frequency were 1100 cycles instead of 550 the wavelength would be 1 foot; if the frequency were 2200 the wavelength would be 6 inches, etc.

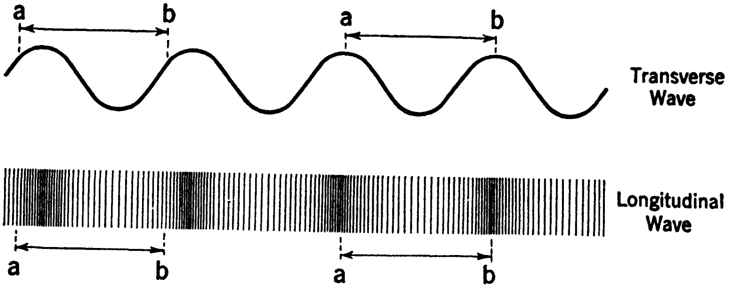


FIG. 142.—A means of showing how wavelength is determined in both a transverse wave and a longitudinal wave, as from *a* to *b*.

If we know the wavelength and also want to know the frequency it is only necessary to find how many times that particular wavelength will go into 1100.

Example:

$$V \text{ (velocity)} = 1100 \text{ feet per second}$$

$$\lambda \text{ (wavelength)} = 2 \text{ feet}$$

$$1100 \div 2 = 550 \text{ waves per second, or frequency.}$$

If we know the wavelength and frequency and wish to find the velocity it is only necessary to multiply one by the other.

Example:

$f$ (frequency) = 550 cycles per second
$\lambda$ (wavelength) = 2 feet
$550 \times 2 = 1100$ feet per second velocity.

Summarizing, we can say:

(1) Velocity of a wave is equal to the wavelength times the frequency, or

(2) Wavelength is equal to the velocity divided by the frequency, or

(3) Frequency is equal to the velocity divided by the wavelength.

The relations between velocity, wavelength and frequency just given are written as follows, using their respective symbols. The basic formula for velocity is stated first. It is to be understood that (1), (2) and (3) express the same relation, the relation being written merely in different forms.

(1) $V = \lambda \times f$ or $V = \lambda f$
(2) $\lambda = V \div f$ or $\lambda = V/f$
(3) $f = V \div \lambda$ or $f = V/\lambda$.

Where:
($\lambda$) = wavelength
($V$) = velocity
($f$) = frequency.

It will be noted that the foregoing formula, written to illustrate how to calculate sound waves, is applicable to all other types of waves. However, when we deal with other waves it must be remembered that the velocity of each type of wave differs, and even the same wave travels at different velocities through various mediums.

**Difference between Noise and Musical Sounds.**—Music is the result of a rapid series of periodic vibrations and, when such vibrations occur at regular intervals, the sounds they produce are pleasing to the ear. Vibrations that are not produced at regular intervals are usually unpleasant in effect. Collisions between heavy objects such as trucks, falling bricks, etc., create vibrations at irregular intervals which are classified as noise.

**Changing Sound to Other Forms of Energy.**—A good example of a commercial process in which sound is converted to other forms of energy is given in the manufacture of modern phonograph records. Figure 143 shows the series of operations performed from the time the original sound is produced at the microphone by the recording artist until the reproduction is heard from the loudspeaker. At the extreme left is a representation of the original sound waves which, striking upon the diaphragm of the *microphone,* produce mechanical motion. This motion is changed to variations in electrical current by the microphone. The *mixer* takes the current from this microphone, and the current from perhaps several other microphones, and varies the intensity that each delivers to the *amplifier.* Several microphones may be used at the same time, especially when an orchestra program is being reproduced, and the mixer serves the purpose of obtaining a balance between the different instruments in the orchestra.

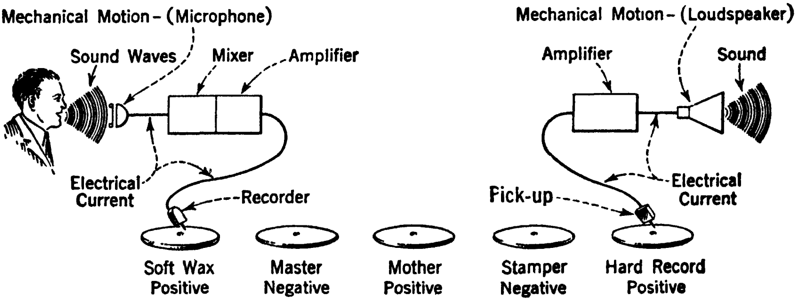


Fig. 143.—Illustrating the step-by-step procedure in the manufacture and reproduction of phonograph records.

After the electric current is amplified about ten million times it is converted back into mechanical motion in the recording cutter which cuts the sound record in a soft wax disc called the *soft wax positive.* By a series of manufacturing processes the successive *platings* and *stampings* of the *master negative, mother positive,* and so on, are produced, ending in the final *hard record positive* which is the phonograph record that we buy from our music dealer. When this record is placed on the turntable of an electric reproducing phonograph (often seen in combination with modern radio sets) the process of recording is reversed. The needle of the *pick-up* unit running in the groove of the record receives mechanical motion that is converted into electric current. This is a good example of the application of the principles of electromagnetic induction where magnetic lines of force are varied by a moving iron arm armature to which the needle is attached and how this, in turn, induces a varying current in the turns of the coils included in this unit. The current is delivered to an amplifier tube and further amplified to a degree that will enable the output of the amplifier which feeds into the loudspeaker to actuate its diaphragm. The diaphragm vibrating in contact with the air produces sound waves which, to all intents and purposes, are an exact copy of the sound waves which were impinged on the diaphragm of the microphone during recording.

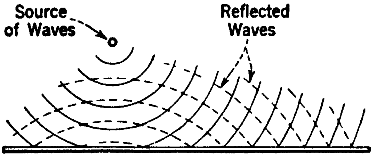


FIG. 144.—Depicting the reflection of sound waves from a plane surface.

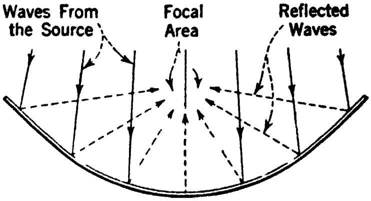


FIG. 145.—Depicting the reflection of sound waves from a curved surface.

Also, the varying electric current that is produced by the microphone can be used, after suitable amplification, to modulate the electromagnetic waves that are sent out from a broadcast transmitting station. The radio receiver in turn reconverts the electromagnetic waves back into sound waves which are, practically speaking, a copy of the original sound received by the microphone in the studio.

**Reflection of Sound.**—When a sound wave strikes a large wall or other similar surface part of it is reflected, part transmitted, and part absorbed. The part that is reflected has a definite shape or form of wave front. This is best shown by referring to Figure 144, which depicts the shape of a sound wave after reflection from a plane surface, such as a wall. From this simple illustration it can be seen that an *echo* is only a reflected sound wave that comes back to the ear after the original sound has died out. If two sounds strike upon the ear with a shorter interval of time between them than about one-tenth of a second, the ear cannot recognize them as distinct or separate sounds. Consequently, since in one-tenth second sound travels about 110 feet ($\frac{1}{10}$ of 1100), one cannot receive an echo from an object that is closer than about 55 feet, a fact which is easily demonstrated.

Reflection of waves from a curved surface sometimes results in a concentration of sound in a small area which is called the *focal area*. This phenomenon is shown graphically in Figure 145, where the sound that originates over a wide area is concentrated and focused by a wall of circular shape into a small "focal area." This is the principle that accounts for the so-called *whispering galleries* where, by standing at a certain place in the building, a listener can hear all sounds that originate in a large area around him. At one time there was such a condition present in the dome of the Capitol at Washington, due to the curvature of the dome itself, and it is said that, at times, a member of the President's cabinet made good use of this natural focal area to overhear various political intrigues.

We stated that in order for a reflecting surface to produce an echo it was necessary that the distance between the reflecting surface and the listener be at least 55 feet. If this distance is less than 55 feet, and if a hall or room uses hard materials for walls, ceiling, and floor, the repeated reflections from these various surfaces come back on the original sound and interfere with it to the extent that a condition known as *reverberation* is brought about. This condition becomes very annoying to speakers and in some cases has been known to render a hall practically unfit for use for any purpose in which sound was involved. The cure for this condition is to use some means for absorbing the excess sound that is represented by reflection. The ideal condition for good hearing would be for the sound to proceed or travel directly from the speaker's mouth to the hearer's ear, with any other sound waves being absorbed or *killed* and not reflected. Since the introduction of Broadcasting and Sound Motion Pictures there has developed a greater necessity for preventing reflection of sound. Extensive experimental and research work is being carried on continuously to determine better methods for obtaining natural reproduction.

One method of eliminating objectionable reverberation is to break up the reflecting surfaces into small sections so that the reflections, by collision with each other, will spend their energy and die out quickly. This is known as *coffering* and is seen at its best in the modern sound motion picture theater, where the construction of the interior is such that thousands of small surfaces are presented to the oncoming sound waves. The method in widest use at present, however, is that of lining the interior of the hall or building with materials which absorb a large amount of the sound energy by converting it into heat. Because energy is indestructible the sound waves must necessarily be changed into some other form of energy and, in this case, they are turned into heat which, of course, is actually an infinitesimal amount. Certain methods have been developed to determine the amount of absorbent material needed for sound-treating a room to reduce excessive reverberation.

Professor Wallace C. Sabine, a pioneer in acoustical work, developed a formula for determining the time of reverberation, that is, the length of time required for a sound to die out in a room. He found, after exhaustive experiments, that a definite relation existed between the time of reverberation in seconds ($t$), the volume of the room in cubic feet ($V$), and the absorbing power per square foot of the different materials present ($a$). Thus: $t = 0.05 \times V \div a$, which is to say that the time a sound will take to die out in a room can be found by multiplying 0.05 by $V$ ($V$ = the volume of the room in cubic feet), divided by $a$ (the absorbing power of the walls, ceilings, floor, contents, and other material in the room). The time of reverberation should be short for good acoustic conditions, hence the volume should not be too large and absorbing materials should be present in sufficient quantity. This is the case in a small room which contains several rugs, curtains, and furniture. However, in a large auditorium with meager furnishings troublesome reverberation will result. Professor Sabine determined the absorbing power of the different materials usually found in auditoriums, calling an open window one square foot in area a perfect absorber of sound, equal to unity or 1. The coefficients for the most common materials calculated by Professor Sabine are given in the following table. In this case the *coefficient* means absorbing power of each material compared with that of an open window of the same size. For example, the twelfth item in the table, or carpet, with ½-inch ozite hairfelt underneath, with a coefficient of 0.25 will absorb only one-fourth as much sound as an open window (item 1), therefore under such conditions three-fourths of the sound would be reflected back into the room.

Sound-absorbing Coefficients For Pitch 512

| Material | | Coefficient per sq ft |
|---|---|---|
| Open window | | 1 00 |
| Plaster | | 027 |
| Wood | | 03 |
| Glass | | 027 |
| Linoleum | | 03 |
| Chair | (each) | 1 |
| Piano | (each) | 6 |
| Table | (each) | 2 |
| Audience | (each) | 4 7 |
| "Acoustex" (1 inch thick) | | 37 |
| Brick Wall | | 032 |
| Carpet | | 25 |
| "Celotex" | | 2 |
| Cork tile | | 03 |
| Curtains in heavy folds | | 40 |
| Marble . | | 01 |
| Ventilators . . . | | 75 |

In calculating the amount of absorbing material needed to reduce the reverberation period to the correct value another arrangement of Sabine's formula may be used. It states that the absorption units needed to reduce reverberation to a certain period is equal to 0.05 × cubic feet volume of room divided by the desired reverberation period.

Taking as a specific case a room in the Smith Music Building at the University of Illinois, it was found by measurement that the volume of the room was 3360 cubic feet and, knowing that one second is a desirable reverberation period for a room of that size, it became necessary merely to multiply 0.05 by 3360 and divide the result by 1, to find that 168 units of absorption were needed. Measuring the different materials present in the room and multiplying each value by the proper coefficient of absorption as shown in the table gave the following results:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Plaster | 1000 | sq. ft. | at | 027 | = | 27 | units |
| Wood (varnished) | 100 | “ “ | “ | 03 | = | 3 | “ |
| Glass | 96 | “ “ | “ | 027 | = | 2 6 | “ |
| Linoleum | 204 | “ “ | “ | 03 | = | 6 1 | “ |
| Chairs | 4 | | “ | 1 | = | 4 | “ |
| Piano | 1 | | “ | 6 | = | 6 | “ |
| Table | 1 | | “ | 2 | = | 2 | “ |
| Table | 1 | | “ | 1 | = | 1 | “ |
| Audience | 3 | | “ | 4 7 | = | 14 1 | “ |
| Heavy coats on rack | | | | | | 5 | “ |
| | | | | | | 59 1 | units |

Thus it was found that 168 units of absorbing material would be needed and 59.1 units were already present in the room. By subtracting the 59.1 units from the 168 units it is seen that 109 additional units must be installed in some manner. Any of the materials listed in the table may be used for this purpose. For example, the material may consist of manufactured sound absorbers such as “Acoustex,” “Celotex,” “Rock Wool,” or materials like rugs, curtains, seat cushions, and the like may be selected. We know that 109 additional units of absorbing material are needed in this particular case and, to determine the exact amount necessary, we divide 109 by the coefficient of the material that is to be used. Rooms and halls of any size can be scientifically treated in this manner so that the desired result will be assured and not left to chance.

**Decibel-Transmission Unit.**—For many years the efficiency of telephone circuits was expressed in terms of the “mile of standard cable,” but with the rapid growth of telephone communication and radio broadcasting a more suitable standard was developed, known as the *transmission unit* or *decibel.* This unit may be defined as the difference between two amounts of sound powers when their intensities are in the ratio of $10^{\cdot 1}$, indicating a ratio in the order of 0.0001 to 0.01. Such a ratio represents the amount of sound energy introduced into the input end of a telephone system as compared to the amount of sound energy reproduced at the other end or output, it being understood, of course, that the actual voice transmission is conveyed through a wire circuit by electrical impulses. Decibel is abbreviated “db.”

Experiments have proven that when the effects which sounds produce on the organism of the ear are compared to actual differences in the magnitude of such sounds the results give a logarithmic curve when plotted on a chart, that is, the curve shows the response of the ear to different degrees in volume or sound power changes. If a certain sound is either very weak or very loud and its intensity is varied by some means it will require a much greater variation in the intensity changes for the average ear to notice that a change has taken place than would be the case for sounds of average loudness. Where a certain sound is steadily increased in volume it generally requires a change of at least 25 per cent in volume before the ear becomes sensitive to that change.

A decibal is used only to express a ratio as mentioned before. For example, suppose the power amplifier of a certain receiver delivers 750 milliwatts of power to a loudspeaker and after adjustment it delivers 1000 milliwatts, then the ratio of this change is 750 to 1000. Although this ratio may appear large in figures yet the actual difference between the two sounds coming from the loudspeaker at different times will be so slight that the ear will not be sensitive enough to detect the difference. Values can be used in the proper formulas and the number of db computed, but it is beyond the scope of this book to treat the decibel and transmission unit in detail.

## PROBLEMS ON CHAPTER VIII

**1.** What is the wavelength of a musical tone of 250 cps, considering the speed of sound in air to be 1100 feet per second?

**2.** (*a*) Are sound waves transverse or longitudinal in character? (*b*) Draw a representation of a transverse wave and one of a longitudinal wave; mark off a wavelength on each.

**3.** What is (*a*) a transverse wave; (*b*) a longitudinal wave?

**4.** What enables you to distinguish between musical instruments of different kinds?

**5.** Draw a simple sketch illustrating a string vibrating and producing the third harmonic.

**6.** What is the frequency range of sound heard by the average person?

**7.** What methods are used to remove excessive reverberation from a room?

**8.** Does sound travel through different mediums with the same velocity?

**9.** (*a*) What is meant by the term rarefaction? (*b*) Compression? (*c*) Reverberation? (*d*) Focal area? (*e*) Coffering?

**10.** Describe briefly how a musical sound is produced by an organ pipe.

# CHAPTER IX

# PREPARATORY MATHEMATICS

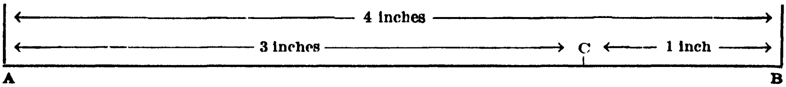
CERTAIN mathematical operations and formulas often slip one's mind, especially if considerable time has elapsed since practicing on, or working out, various problems. A working knowledge of mathematics is essential; without such knowledge the student cannot expect to make any progress whatever with technical or scientific subjects, even from the practical viewpoint.

Mathematics may be compared to a language because it is composed of numerous terms, expressions, and operations, all of which are founded on well-established rules and laws. A special effort should be made to learn the meaning of the various terms and to understand thoroughly the rules and laws. Read through these pages frequently; review and study any points which are not firmly fixed in your mind. Occasional reviews and practical application of the different principles are the only possible means by which you can cultivate your memory, thus enabling you to retain sufficient information to be of real value to you. As a rule, the principles of mathematics become very simple to most persons after they apply themselves to the task of studying the subject.

Guesswork in mathematics is a dangerous practice, and if indulged in very often it may block your progress; at least it will cause you to be careless and make mistakes and, furthermore, you are apt to waste considerable time. To get the most out of this work it is advisable to learn and understand the rules first, and then practice them by working out numerous problems until they become absolutely familiar to you. It is not too much to ask of anyone who intends to educate himself above the average to work out at least twenty-five problems relating to a particular mathematical principle. It should be remembered, however, that in order to understand thoroughly the principles involved, each problem must present a slightly different appearance, which may be accomplished by using different numerical values and changing the wording of each question.

## FRACTIONS

**Definitions.**—A line is said to be the shortest distance between two points. For convenience we designate a point in space by a letter. The small sketch below shows a straight line drawn between *A* and *B*. We call this line *AB*. The distance between these two points is measured in terms of some standard unit such as inches, centimeters, yards or miles. *AB* is seen to be 4 inches in length.



Any portion of the line *AB* which is less than the total length is said to be a fractional part of the whole. Thus if point *C* is placed on the line *AB* 3 inches from *A*, the portion *AC* will represent $\frac{3}{4}$ of the total line. *CB* will represent only $\frac{1}{4}$ of the whole. It will be seen that *CB* is only $\frac{1}{3}$ as long as *AC*. The line *AB* may be considered to be made up of a number of individual units. If it is divided into $\frac{1}{2}$-inch sections there will be 8 of these sections contained in the line.

Each of the proportional parts may be expressed numerically with reference to the total line. Thus *AC* is called $\frac{3}{4}$ of *AB*. *CB* is called $\frac{1}{4}$ of *AB*. *CB* is $\frac{1}{3}$ of *AC*. These expressions are termed *fractions*. The number above the line is called the *numerator*; the number below the line is termed the *denominator*. The denominator designates the number of parts into which the whole is divided. The numerator indicates the number of the proportionate parts which are contained in the portion of the line being considered.

**Reduction of Fractions.**—A fraction is said to be reduced to its lowest terms when the numerator and the denominator are not divisible by the same number without a remainder.

Four-eighths, written $\frac{4}{8}$, can be reduced to a lower term by dividing both the numerator and denominator by 2. The fraction then becomes $\frac{2}{4}$. It may be reduced still further by dividing again by 2, resulting in the fraction $\frac{1}{2}$. This cannot be again reduced. Therefore $\frac{4}{8}$ is said to be reduced to its lowest term when it is written as $\frac{1}{2}$.

The number by which the numerator and denominator is divided is called the *common divisor*. The following are a few examples:

$\frac{3}{6}$ can be reduced to $\frac{1}{2}$, the common divisor being 3.
$\frac{14}{16}$ can be reduced to $\frac{7}{8}$, the common divisor being 2.
$\frac{3}{5}$ cannot be reduced.

### EXERCISE 1

1. What part of a dollar is ten cents?
2. What part of a dollar is twenty-five cents?
3. Write eighty cents as a fractional part of a dollar.

Reduce the following fractions to their lowest terms:

4. $\frac{14}{18}$
5. $\frac{21}{35}$
6. $\frac{24}{32}$
7. $\frac{18}{21}$
8. $\frac{27}{45}$
9. $\frac{63}{126}$
10. $\frac{17}{68}$

**Changing Fractions.**—Fractions may be changed in form by multiplying both the numerator and the denominator by the same number. The actual value of the fraction will not be changed.

$$\frac{3}{4} \times \frac{2}{2} = \frac{6}{8} \qquad \frac{6}{10} \times \frac{3}{3} = \frac{18}{30}$$

To change a fraction to an equivalent fraction, that is, one having a different denominator, it is necessary to form an equation in the following manner:

EXAMPLE: $\frac{1}{2} = \frac{?}{64}$

Let $x$ represent the number represented by the question mark (?) Cross multiply the terms of the equation, as follows:

$$2 \times x = 64 \times 1$$

$$2x = 64$$

If 2 times $x$ is equal to 64, obviously $x$ must be $\frac{1}{2}$ of 64,

$$\text{or,} \quad x = \frac{64}{2} = 32$$

Hence, the number 32 will replace the question mark in our original equation for changing a fraction to an equivalent fraction, or

$$\frac{1}{2} = \frac{32}{64}$$

### EXERCISE 2

1. $\frac{4}{5} = \frac{?}{50}$
2. $\frac{3}{16} = \frac{?}{64}$
3. $\frac{4}{12} = \frac{?}{24}$
4. $\frac{5}{7} = \frac{?}{49}$
5. $\frac{4}{9} = \frac{?}{36}$
6. $\frac{3}{13} = \frac{?}{78}$

**The Common Denominator.**—It is convenient and necessary in the case of the addition or subtraction of fractions to change the denominators of all the fractions to a common number called the *common denominator*.

**Example:** $\frac{1}{4} + \frac{5}{16} = ?$

In order to add these fractions we must make them proportionate parts of a common whole. It will be necessary to expand $\frac{1}{4}$ to its equivalent fraction having 16 as its denominator.

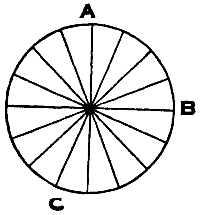
$$\frac{1}{4} = \frac{?}{16}, \text{ which may be written } \frac{1}{4} = \frac{x}{16}.$$

By cross multiplying we have $4 \times x = 16 \times 1$.

$$4x = 16, \text{ or } x = \frac{16}{4}, \text{ or } x = 4$$

Hence, the number 4 will replace the question mark or $x$.

Therefore, $\frac{1}{4} = \frac{4}{16}$



Now we may consider a circle divided into 16 equal parts as shown.

One-fourth of this circle is equivalent to $\frac{4}{16}$. This portion is indicated as the part $AB$. Adding five more units, or $\frac{5}{16}$, gives us an area inclosed by $ABC$. This total is seen to be nine sections, or $\frac{9}{16}$ of the whole circle, as proven below.

Since $\frac{1}{4} = \frac{4}{16}$, then

$$\frac{1}{4} + \frac{5}{16} = \frac{4}{16} + \frac{5}{16} = \frac{9}{16}.$$

Also, fractions may be subtracted when their denominators are the same, as follows:

**Example:** $\frac{9}{16} - \frac{1}{4} = ?$

It is first necessary to change $\frac{1}{4}$ in the foregoing equation to an equivalent fraction having 16 as a denominator, thus

$$\frac{1}{4} = \frac{?}{16}. \qquad 4 \times x = 16 \times 1, \text{ or } 4x = 16, \text{ or } x = \frac{16}{4}, \text{ or } x = 4.$$

$$\text{hence } \frac{1}{4} = \frac{4}{16}$$

Now, $\frac{9}{16} - \frac{1}{4} = \frac{9}{16} - \frac{4}{16} = \frac{5}{16}.$

To subtract or add fractions having denominators that are not evenly divisible into one another, it is necessary to obtain a least common denominator.

For instance, we could not add $\frac{1}{4}$ of a circle divided into 4 parts to $\frac{1}{3}$ of a different circle divided into 3 parts without establishing a common circle. The following shows how fractions having denominators that are not evenly divisible into one another are added:

**Example:** $\frac{1}{3} + \frac{1}{4} = ?$

The smallest number which is divisible by both 3 and 4 without a remainder is 12, hence 12 is the least common denominator.

$$\frac{1}{3} = \frac{?}{12}, \text{ or } 3x = 12, \text{ or } x = 4, \text{ hence } \frac{1}{3} = \frac{4}{12}$$

$$\frac{1}{4} = \frac{?}{12}, \text{ or } 4x = 12, \text{ o } x = 3, \text{ hence } \frac{1}{4} = \frac{3}{12}$$

Therefore, substituting equivalent fractions and adding, we have

$$\frac{1}{3} + \frac{1}{4} = \frac{4}{12} + \frac{3}{12} = \frac{7}{12}$$

Likewise, after obtaining equivalent fractions, we may subtract in this instance as follows:

$$\frac{1}{3} - \frac{1}{4} = \frac{4}{12} - \frac{3}{12} = \frac{1}{12}$$

Where more than two fractions are to be added or subtracted the same rule applies; you must obtain a least common denominator for the denominators that are not evenly divisible into one another, thus

$$\frac{9}{16} + \frac{1}{8} + \frac{1}{4} = \frac{9}{16} + \frac{2}{16} + \frac{4}{16} = \frac{15}{16}$$

It will be seen that from the above example the process of addition of fractions is one of changing the fractions to equivalent fractions having a like denominator and adding the numerators.

It is often found that after adding fractions we get a sum greater than unity, or 1, which means that the numerator is greater than the denominator. A fraction of this kind is called an *improper fraction.* For example

$$\frac{14}{16} + \frac{1}{4} = \frac{14}{16} + \frac{4}{16} = \frac{18}{16}, \text{ an improper fraction.}$$

An improper fraction can be reduced to its lowest terms by dividing the numerator by the denominator as follows:

$$\frac{18}{16} = 1\frac{2}{16} = 1\frac{1}{8}.$$

This answer, $1\frac{1}{8}$, is called a *mixed number* because it contains a whole number and a fraction.

**Addition of Mixed Numbers.**—Mixed numbers may be added in either of two ways.

The first method is by changing each mixed number to an improper fraction which may then be reduced or expanded to a common denominator. The following illustrates this:

$$1\frac{5}{16} + 3\frac{1}{2} + 2\frac{1}{8} = \frac{21}{16} + \frac{7}{2} + \frac{17}{8} = \frac{21}{16} + \frac{56}{16} + \frac{34}{16} = \frac{111}{16} = 6\frac{15}{16}.$$

The first term, $1\frac{5}{16}$, is changed to the improper fraction $\frac{21}{16}$ by adding the number of sixteenths indicated by the whole number 1, to the number of sixteenths contained in the fraction. Considering the circle again, the whole number 1 represents the complete circle which is composed of 16 parts or $\frac{16}{16}$.

$1 = \frac{16}{16} = \frac{8}{8} = \frac{4}{4} = \frac{2}{2}$ or any other fractional expression whose numerator is the same as the denominator.

In the second term, $3\frac{1}{2}$, we may write 3 as $\frac{6}{2}$ and it is necessary to add to this the fractional portion which is $\frac{1}{2}$, hence $3\frac{1}{2} = \frac{6}{2} + \frac{1}{2} = \frac{7}{2}$.

The third term, $2\frac{1}{8}$, may likewise be written as $\frac{16}{8} + \frac{1}{8} = \frac{17}{8}$.

The second method of adding mixed numbers is to treat the whole numbers and the fractions as separate terms. An example of this is given as follows:

$$1\tfrac{5}{16} + 3\tfrac{1}{2} + 2\tfrac{1}{8} = (1 + 3 + 2) + (\tfrac{5}{16} + \tfrac{1}{2} + \tfrac{1}{8}) = 6 + (\tfrac{5}{16} + \tfrac{8}{16} + \tfrac{2}{16}) = 6\tfrac{15}{16}.$$

### EXERCISE 3

1. $\frac{1}{4} + \frac{3}{8} = ?$
2. $\frac{9}{16} + \frac{3}{16} = ?$
3. $\frac{5}{12} + \frac{1}{3} = ?$
4. $\frac{1}{8} + \frac{3}{12} = ?$
5. $\frac{15}{16} - \frac{5}{8} = ?$
6. $\frac{8}{9} - \frac{2}{3} = ?$
7. $\frac{7}{11} - \frac{4}{22} = ?$
8. $\frac{13}{15} - \frac{2}{5} = ?$
9. $\frac{1}{6} + \frac{2}{3} + \frac{5}{12} = ?$
10. $\frac{3}{7} + \frac{10}{21} + \frac{1}{14} = ?$
11. $\frac{13}{15} + \frac{2}{5} + \frac{1}{3} = ?$
12. $\frac{9}{10} + \frac{1}{20} + \frac{1}{5} = ?$
13. $1\frac{5}{8} + 3\frac{9}{10} + 1\frac{1}{5} = ?$
14. $2 + 1\frac{5}{9} + 3\frac{1}{3} = ?$
15. $4\frac{2}{3} + 1\frac{5}{6} + \frac{5}{9} = ?$

**Easy Methods for Finding L. C. D.**—It is not always possible to find the least common denominator by a mere observation of the numbers. There are different methods to find the L. C. D. (least common denominator).

One method is explained as follows where the denominators are multiplied together to obtain a number which will contain all denominators.

$$\frac{1}{11} + \frac{6}{13} = ?$$

$$11 \times 13 = 143$$

Hence $\frac{1}{11} = \frac{13}{143}$ and $\frac{6}{13} = \frac{66}{143}$

Therefore $\frac{13}{143} + \frac{66}{113} = \frac{79}{143}$

A method of division may also be used to find the L. C. D.

Below we show how to find the L.C.D. of $\frac{5}{16} + \frac{1}{9} + \frac{3}{15}$. In each instance the number on the left-hand margin is one that is divisible into one or more of the denominators written within the bracket.

$$\begin{array}{r|rrr}
3 & 16 & 9 & 15 \\ \hline
4 & 16 & 3 & 5 \\ \hline
2 & 4 & 3 & 5 \\ \hline
 & 2 & 3 & 5
\end{array}$$

$3 \times 4 \times 2 \times 2 \times 3 \times 5 = 720$. This is the L.C.D.

**Multiplication of Fractions.**—This is done by placing the result obtained after multiplying the numerators together over the result obtained after multiplying the denominators together. Several examples which include fractions and whole numbers follow:

(1) $\frac{1}{5} \times \frac{3}{7} = \frac{3}{35}$

(2) $\frac{5}{8} \times \frac{5}{9} = \frac{25}{72}$

(3) $\frac{4}{5} \times 3 \times \frac{9}{10} = \dfrac{4 \times 3 \times 9}{5 \times 10} = \dfrac{108}{50} = 2\frac{8}{50} = 2\frac{4}{25}$

(4) $1\frac{3}{5} \times \frac{4}{3} \times 2 = \frac{8}{5} \times \frac{4}{3} \times 2 = \dfrac{8 \times 4 \times 2}{5 \times 3} = \dfrac{64}{15} = 4\frac{4}{15}$

By a cancellation process the work of multiplying fractions may be simplified. The following examples show how common factors of the numerators and denominators are canceled and the remainders multiplied together.

(1) $$\frac{1}{2} \times \frac{4}{15} \times \frac{5}{16} = \frac{1}{2} \times \underset{3}{\frac{\cancel{4}}{\cancel{15}}} \times \underset{4}{\frac{\cancel{5}}{\cancel{16}}} = \frac{1}{2 \times 3 \times 4} = \frac{1}{24}$$

(2) $4\frac{2}{3} \times 6\frac{2}{5} \times \frac{15}{16} = \frac{14}{3} \times \frac{32}{5} \times \frac{15}{16} =$

$$\frac{14}{\underset{1}{\cancel{3}}} \times \frac{\overset{2}{\cancel{32}}}{\cancel{5}} \times \frac{\overset{\cancel{3}}{\cancel{15}}}{\cancel{16}} = \frac{14 \times 2}{1} = \frac{28}{1} = 28.$$

## EXERCISE 4

**1.** $\frac{4}{9} \times \frac{1}{3} = ?$

**2.** $\frac{3}{7} \times \frac{1}{8} = ?$

**3.** $\frac{1}{6} \times \frac{1}{4} = ?$

**4.** $\frac{5}{16} \times \frac{1}{3} = ?$

**5.** $1\frac{2}{3} \times 3\frac{1}{5} \times \frac{3}{4} = ?$

**6.** $3\frac{1}{2} \times \frac{4}{5} \times \frac{5}{3} = ?$

**7.** $2\frac{1}{6} \times 1\frac{1}{2} \times 3\frac{1}{6} \times 7 = ?$

**Division of Fractions.**— To divide fractions the divisor is inverted and treated exactly as a multiplier, thus

$$\frac{1}{2} \div \frac{1}{4} = \frac{1}{\cancel{2}} \times \frac{\overset{2}{\cancel{4}}}{1} = \frac{2}{1} = 2$$

The foregoing tells us that $\frac{1}{4}$ is contained in $\frac{1}{2}$ exactly two times.

(1) $$\frac{5}{16} \div \frac{3}{4} = \frac{5}{\underset{4}{\cancel{16}}} \times \frac{\cancel{4}}{3} = \frac{5}{12}$$

(2) $1\frac{5}{16} \div 1\frac{2}{3} = \frac{21}{16} \div \frac{5}{3} = \frac{21}{16} \times \frac{3}{5} = \frac{63}{80}$

## EXERCISE 5

**1.** $\frac{1}{3} \div \frac{1}{2} = ?$

**2.** $\frac{1}{5} \div \frac{2}{3} = ?$

**3.** $\frac{5}{6} \div \frac{6}{5} = ?$

**4.** $\frac{3}{8} \div \frac{5}{16} = ?$

**5.** $6\frac{1}{3} \div 2\frac{1}{6} = ?$

**6.** $4\frac{2}{3} \div \frac{17}{16} = ?$

**7.** $2\frac{2}{5} \div 4\frac{1}{2} = ?$

**8.** $1\frac{14}{15} \div 3\frac{1}{8} = ?$

## DECIMAL FRACTIONS

**Decimal Fractions.**—Fractions that have 10 or an even multiple of 10 for a denominator are called *decimal fractions.* In this section we deal with such fractions, which are expressed in a manner entirely different from ordinary fractions, and also fractions which may be expanded to an even multiple of 10.

With the decimal point as a reference mark, numbers to the right and left of the decimal point are given special designation as follows:

| Millions | Hundred Thousands | Ten Thousands | Thousands | Hundreds | Tens | Decimal Point | Tenths | Hundredths | Thousandths | Ten Thousandths | Hundred Thousandths | Millionths |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | . | 0 | 0 | 0 | 0 | 0 | 0 |

Thus a number appearing 3 places to the right of the decimal point, such as 0.003, would be read "three thousandths" and would, in fraction form, appear as $\frac{3}{1000}$.

Each of the fractions $\frac{3}{10}$, $\frac{6}{100}$, and $\frac{13}{10000}$ fulfil the requirement of a decimal fraction in that their denominators are evenly divisible by 10. These may be written

$$\frac{3}{10} = 0.3 \qquad \frac{6}{100} = 0.06 \qquad \frac{13}{10000} = 0.0013$$

It will be seen that the last number in a numerator appears as many places to the right of the decimal point as there are ciphers in the denominator.

When an expression contains a whole number followed by a decimal fraction the word "and" is used to indicate the decimal point, for instance, 6.275 is read "six and two hundred seventy-five thousandths."

An expression such as 0.00025 is often read "triple oh two five."

### EXERCISE 1

Read each of the following:

**1.** 0.016
**2.** 0.0601
**3.** 0.20601
**4.** 0.00002
**5.** 216.7403
**6.** 17.000001

Write the following as decimal fractions:

**7.** Two and seven hundred six thousandths.
**8.** Four hundred and three millionths.
**9.** Twenty and two millionths.
**10.** Three hundred thousand and three hundred thousandths.

**Addition of Decimals.**—To add decimals place the numbers under each other so that the decimal points form a vertical line and proceed as in the addition of whole numbers.

EXAMPLE:

$$\begin{array}{r}
.0025\phantom{0} \\
1001.01016 \\
.003\phantom{00} \\
501.305\phantom{00} \\
\hline
1502.32066
\end{array}$$

**Subtraction of Decimals.**—Place the numbers so that the decimal points are in line and treat as whole numbers.

EXAMPLE 1:

$$\begin{array}{r}
301.00602 \\
27.99821 \\
\hline
273.00781
\end{array}$$

EXAMPLE 2:

$$\begin{array}{r}
62.001731 \\
6.000501 \\
\hline
56.001230
\end{array}$$

**Multiplication of Decimals.**—Multiply the decimals as in the case of whole numbers and in the product point off as many places from the right as there are decimal places in both of the factors taken together.

EXAMPLE 1:

$$\begin{array}{r}
62.031 \\
.273 \\
\hline
186093 \\
434217\phantom{0} \\
124062\phantom{00} \\
16.934463
\end{array}$$

Note in the above that since there are six decimal places in the two factors we point off six places from the right to locate the decimal point.

EXAMPLE 2:

$$\begin{array}{r}
30.1003 \\
1.206 \\
\hline
1806018 \\
6020060\phantom{0} \\
301003\phantom{00} \\
\hline
36.3009618
\end{array}$$

## EXERCISE 2

**1.** $2.601 + 32.01 + 0.0062 = ?$
**2.** $36.0061 + 16.003 + 2.0101 = ?$
**3.** $76.402 + 13100 + 2.0013 = ?$
**4.** $6607.2 + 0.003 + 0.0004 = ?$
**5.** $26.001 - 6.03216 = ?$
**6.** $1 - 0.2061 = ?$
**7.** $13.6152 - 0.0721 = ?$
**8.** $23.421 \times 6.001 = ?$
**9.** $3101 \times 0.625901 = ?$
**10.** $23.41 \times 0.0002 = ?$
**11.** $1 \times 0.063217 = ?$
**12.** $89.089 \times 0.01101 = ?$

**Division of Decimals.**—The division of decimals requires a very careful study of the placement of the decimal point. Where the divisor is a decimal number it is convenient, after first writing it down in the form of a fraction, to multiply both the numerator and the denominator by 10, or by some multiple of 10 great enough to make the denominator a whole number and this will enable you to remove the decimal point from the denominator. In other words, you form an equivalent fraction consisting of whole numbers only. Remember, the value of a fraction is not changed if the numerator and denominator are both multiplied by the same number.

EXAMPLE 1: Divide 2314 by .016.

This can be written in fractional form, as $\dfrac{2314}{.016}$

$$\frac{2314}{.016} \times \frac{1000}{1000} = \frac{2314000}{16}$$

The foregoing operation removed the decimal and the solution is found by simple division, thus

$$\begin{array}{rrl}
 & 144625 & \textit{Quotient} \\
\textit{Divisor}\ 16 & \big)\overline{2314000} & \textit{Dividend} \\
 & \underline{16}\phantom{00000} & \\
 & 71\phantom{0000} & \\
 & \underline{64}\phantom{0000} & \\
 & 74\phantom{000} & \\
 & \underline{64}\phantom{000} & \\
 & 100\phantom{00} & \\
 & \underline{96}\phantom{00} & \\
 & 40\phantom{0} & \\
 & \underline{32}\phantom{0} & \\
 & 80 & \\
 & 80 &
\end{array}$$

It will be seen that the actual changing of the fraction can be done by inspection, as follows, without resorting to the method of multiplication as just explained. An example and explanation of this method follows:

$$2314 \div .016$$

$$.016_{\times}\big|\,2314.000_{\times}$$

Moving the decimal point in the divisor three places to the right to the point indicated by x, is equivalent to multiplying by 1000. The decimal point in the dividend which would normally be placed after the 4 must also be moved three places to the right and to do this, in this case, where there are no significant figures after the decimal point in the dividend, it is necessary to add three zeros, placing the decimal point after the last one as indicated by x. To properly place the decimal point in the quotient it would only be necessary to locate it directly above the x, or the new decimal point in the dividend.

EXAMPLE 2: Divide 29.2614 by 2.0901

$$\begin{array}{r|l}
 & \phantom{29.26}14.\ \ \textit{Quotient} \\ \hline
\textit{Divisor}\ \ 2.0901_{\times} & 29.2614_{\times}\ \ \textit{Dividend} \\
 & \underline{20\,901} \\
 & \ \ 8\,3604 \\
 & \ \ 8\,3604
\end{array}$$

In the foregoing case it was unnecessary to add ciphers in order to move the decimal point four places to the right because there were four significant figures after the decimal point in the dividend as it appeared originally.

EXAMPLE 3: Divide .00216 by 3.16

$$\begin{array}{r|l}
 & \phantom{.}.00068\ \ \textit{Quotient} \\ \hline
\textit{Divisor}\ \ 3.16_{\times} & .00_{\times}21600 \\
 & \ \ \ \underline{1896} \\
 & \ \ \ \ 2640 \\
 & \ \ \ \ \underline{2628} \\
 & \ \ \ \ \ \ 112\ \ \textit{Remainder}
\end{array}$$

The quotient in the foregoing is only an approximation of the correct answer because we have a remainder of 112. More ciphers would have to be added to the dividend and the computation carried out further if a quotient nearer the exact answer, or the exact answer itself were desired.

## EXERCISE 3

1. $.0206 \div 31 = ?$
2. $21.0001 \div 3.001 = ?$
3. $.0206 \div 60.13 = ?$
4. $71.95 \div 32.41 = ?$
5. $6010.03 \div 4.295 = ?$
6. $37.1618 \div .01001 = ?$
7. $.00132 \div 621 = ?$
8. $345 \div 62.96 = ?$

**In the above exercises carry the answers to three significant figures after the decimal point.**

**Common Fractions Reduced to Decimals.**—Common fractions may be reduced to decimal form by dividing the numerator by the denominator.

Example 1: $\frac{3}{4} = 3 \div 4$

$$\text{Work:}\quad \begin{array}{r|r} & .75 \\ \hline 4 & 3.00 \\ & \underline{2\,8\phantom{0}} \\ & 20 \\ & \underline{20} \end{array}$$

Hence, $\frac{3}{4} = .75$

Example 2: $\frac{21}{25} = 21 \div 25$

$$\text{Work:}\quad \begin{array}{r|r} & .84 \\ \hline 25 & 21.00 \\ & \underline{20\,0\phantom{0}} \\ & 1\,00 \\ \cline{2-2} & 1\,00 \end{array}$$

Hence, $\frac{21}{25} = .84$

### EXERCISE 4

Change the following fractions to decimals and add to find the result.

1. $\frac{1}{4} + \frac{1}{16} + \frac{3}{7} + \frac{4}{9} = ?$
2. $\frac{1}{9} + \frac{3}{16} + \frac{7}{11} + \frac{21}{31} = ?$
3. $\frac{1}{17} + \frac{1}{31} + \frac{1}{11} = ?$

Change the following fractions to decimals and divide to find the result.

4. $\frac{6}{31} \div \frac{4}{11} = ?$
5. $6\frac{2}{3} \div \frac{3}{25} = ?$
6. $17\frac{1}{5} \div \frac{2}{9} = ?$
7. $\frac{3}{16} \div 3\frac{1}{3} = ?$

In the above exercises carry the answer to three significant figures after the decimal point.

## SQUARE ROOT

**Square Root Defined.**—The term "root" is best explained by means of an illustration before the definition itself is given.

Suppose we separate 4 into two equal factors, 2 and 2. This shows that $4 = 2 \times 2$ and that one of the factors 2 is the square root of 4. By inspection it will be clearly seen that this is just the reverse or opposite process to that used when obtaining the power of a number. Let us give another illustration. Separate 16 into two equal factors, 4 and 4. By multiplying 4 by itself, we have $4 \times 4 = 16$, or $16 = 4 \times 4$. Hence, 4 is the square root of 16.

Square root is defined as follows: *The square root of any number is one of the two equal factors into which the number is divided.*

**The Radical Sign.**—To indicate a power we make use of an exponent and to indicate a root we make use of a special sign, called the *radical* sign. The radical sign is written $\sqrt{\ }$ and is followed by a *vinculum*, which is a straight line, $\sqrt{\quad}$, drawn as an extension to the radical. In all cases the vinculum is used to show to what extent the radical sign affects the expression, or number, before which it appears.

For example, the number 16 when considered entirely by itself simply means 16 units. However, when a radical sign appears before the number 16, or $\sqrt{16}$, it means that the square root of 16 is to be taken.

In the following expression $\sqrt{16} \times 5 = 20$, the radical sign affects only 16, and not 5, since the vinculum extends only over 16.

A small number placed in the $\sqrt{\ }$ shaped opening of a radical is called the **index** and indicates what root is to be taken. Thus, $\sqrt[3]{125}$ would tell us at once that the cube root of 125 is to be found, and $\sqrt[4]{192}$ indicates that the fourth root of 192 is to be found. Inasmuch as square root is more frequently used in ordinary computations it is the custom in this case to omit the figure 2 from the radical. Therefore, to indicate square root, a radical with its associated vinculum is written $\sqrt{\quad}$ without an index number.

For example, the square root of 16 is always written as $\sqrt{16}$, and never as $\sqrt[2]{16}$. However, bear in mind that if any root higher than 2 is desired the index must always be written.

Summing up all the facts in the foregoing paragraphs we find that "Involution" is used when the power of a certain number is to be found whereas, "Evolution" is used when the root of a certain number is to be found.

**Perfect Squares.**—There are only a very few numbers that are perfect squares. For example, between 1 and 100 there are only nine perfect squares, and between 1 and 1000 there are but thirty-one perfect squares.

The following list includes all the numbers between 1 and 1000 that are **perfect squares**: 1, 4, 9, 16, 25, 36, 49, 64, 81, 100, 121, 144, 169, 196, 225, 256, 289, 324, 361, 400, 441, 484, 529, 576, 625, 676, 729, 784, 841, 900, 961.

If we extract the square root of any of the above numbers we will obtain a result which is a whole number.

**How to Find the Square Root of a Perfect Square.**—

EXAMPLE: Find the square root of 625.

$$\sqrt{625}$$

*First Step:* Write down the statement of the problem, as shown above, by using the radical sign. Next separate the number 625 into periods of two digits each as indicated below where the radical sign is omitted when working out the problem. Begin at the right of the number as follows and place a small mark between each pair of figures or digits to indicate this separation. (*Note:* The term "digit" and "figure" are used here interchangeably.) The small mark or stroke is written thus:

6′25

It is found that when 625 is separated in this way it contains two periods, and from this we know that only two figures will appear in the root, or answer.

$$\begin{array}{r|l} 6'25 & \underline{\quad} \end{array}$$

*Second Step:* Now select the largest figure, which when squared (that is, the figure selected is multiplied by itself) will be equal to or less than the left-hand period, or 6. Suppose we try 1. Squaring 1 we have 1 × 1 = 1; this result is obviously too small. Let us try 3. Squaring 3 we have 3 × 3 = 9. But, we find 9 to be too large, for it is greater than the left-hand period. Try 2 this time. Squaring 2 we have 2 × 2 = 4. We find that 2 is the correct figure to use, according to our rule, because 2 squared, or 4, is the highest number below 6 which when squared will not be greater than 6.

*Third Step:* Place 4 under 6, and then place the square root of 4, or 2, in the bracket to the right which is drawn expressly for this purpose, as follows:

$$\begin{array}{r|l} 6'25 & \underline{2\quad} \\ \underline{4}\phantom{25} & \end{array}$$

*Fourth Step:* Subtract 4 from 6 and write down the remainder as you would do in any regular process of substraction, thus:

$$\begin{array}{r|l} 6'25 & \underline{2\quad} \\ \underline{4}\phantom{25} & \\ 2\phantom{25} & \end{array}$$

*Fifth Step:* Bring down the next period of the number, or 25. Our computation will now look as follows:

$$\begin{array}{r|l} 6'25 & \underline{2\quad} \\ \underline{4\phantom{25}} & \\ 225 & \end{array}$$

*Sixth Step:* Now multiply the root 2, just found, by 2. Write down this work at one side of the paper, as follows:

$$2 \times 2 = 4 \qquad \begin{array}{r|l} 6'25 & \underline{2\quad} \\ \underline{4\phantom{25}} & \\ 225 & \end{array}$$

*Seventh Step:* The figure 4, just found by multiplying the root (2) by 2, is called the *trial divisor*. We must now divide the remainder 225 by 4. Remember, that at this point you always disregard the right-hand figure in the remainder, which is 5 in this example. Actually, then, we divided 22 by 4, and not 225 by 4. Hence, 225 ÷ 4 = 5. We find that we have a quotient 5 with a remainder. Disregard the remainder but use the quotient 5, and annex it to the 4 which was found in the sixth step by doubling the root. Our example and work will appear as follows:

2 × 2 = 4, annex 5 makes 45

```
6'25|2
4   ‾‾‾
‾‾‾
225
```

*Eighth Step:* The number 45 just found is called the *true* or *complete divisor.* The steps explained above are now repeated. Accordingly, we divide 225 by 45. By simple division we find that 225 ÷ 45 = 5. This figure 5 becomes the second digit in the root and, therefore, it is written in the bracket to the right of the first figure in the root, or 2. The root now contains two figures, or digits, 2 and 5.

```
6'25|25
4   ‾‾‾‾
‾‾‾
225
225
‾‾‾
```

This completes the necessary steps in the working out of our example, and we find that 25 is the square root of 625. Since there is no remainder we call this a perfect square.

*Proof:* To check our computation and prove that 25 is the correct root we merely have to multiply 25 by itself, that is, we square 25. If the number itself and the root, when squared, are equal then you know that you have the correct answer. Thus, $25^2 = 25 \times 25 = 625$.

**How to find the Square Root of a Large Number.**—The examples in square root that have been previously worked out consisted of numbers having only three digits, all of the numbers being perfect squares. This section will also deal with perfect squares, but this time we will work with numbers consisting of more than three digits so that the square root of any large number may be found. Study the following worked-out example.

EXAMPLE: Find the square root of 516961.

Mark off the periods to include two digits each, thus:

```
51'69'61 |
          ‾‾‾
```

The number whose square is equal to, or less than the first period, 51, is found by trial to be 7.

$7 \times 7 = 49$

Since 7 is to be the first figure in the root, it is placed in the bracket to the right of the number, as shown below:

```
51'69'61|7
         ‾‾
```

Square the root 7, just found (that is, multiply 7 by itself, or 7 × 7) and place the result, 49, under the first period of the number, 51, and then subtract 49 from 51.

$$\begin{array}{ll} 7 \times 7 = 49 & 51'69'61\,|\underline{\,7\,} \\ & \underline{49} \\ & \;\;2 \end{array}$$

After subtracting, we get a remainder of 2, and to this we annex the next period of the number, 69, thus giving us a remainder of 269.

$$\begin{array}{ll} 7 \times 7 = 49 & 51'69'61\,|\underline{\,7\,} \\ & \underline{49\quad} \\ & \;\;269 \end{array}$$

Multiplying the root 7 by 2 gives us a trial divisor of 14.

$$\begin{array}{ll} 7 \times 7 = 49 & 51'69'61\,|\underline{\,7\,} \\ 7 \times 2 = 14 & \underline{49\quad} \\ & \;\;269 \end{array}$$

By division we find that the trial divisor 14 will go into the remainder 269 only once. Note that we disregard the right-hand figure 9 in 269, and, therfore, we really divide 26 by 14, as follows:

$$26\cancel{9} \div 14 = 1 +$$

Annex the 1 to the trial divisor 14, thus making 141 the complete divisor

$$\begin{array}{ll} 7 \times 7 = 49 & 51'69'61\,|\underline{\,7\,} \\ 7 \times 2 = 14 \text{ annex } 1 = 141 & \underline{49\quad} \\ & \;\;269 \end{array}$$

Next divide 269 by the complete divisor 141 and use the result as the next figure of the root.

$$269 \div 141 = 1 +$$

We find 1 to be the next figure of the root, and, therefore, 1 is written to the right of 7 as shown below.

$$\begin{array}{ll} 7 \times 7 = 49 & 51'69'61\,|\underline{\,71\,} \\ 7 \times 2 = 14 \text{ annex } 1 = 141 & \underline{49\quad} \\ & \;\;269 \end{array}$$

Multiply 1 by 141 = 141. Write 141 under 269 and then subtract. This leaves a remainder of 128. The next period of the number, or 61, is now brought down and annexed to 128,

$7 \times 7 = 49$

$7 \times 2 = 14$ annex $1 = 141$

$$\begin{array}{l|l} 51'69'61 & \underline{71} \\ \underline{49} & \\ \ 269 & \\ \ 141 & \\ \ 12861 & \end{array}$$

Multiply the entire root 71 by 2 in order to obtain a product that will be the next trial divisor. This product is 142.

$7 \times 7 = 49$

$7 \times 2 = 14$ annex $1 = 141$

$71 \times 2 = 142$

$$\begin{array}{l|l} 51'69'61 & \underline{71} \\ \underline{49} & \\ \ 269 & \\ \ 141 & \\ \ 12861 & \end{array}$$

Now divide 12861 by 142, but first disregard the extreme right-hand digit 1 of 12861. In reality, then, we divide 1286 by 142, or

$$1286\cancel{1} \div 142 = 9$$

After annexing the 9 to 142, we get 1429, the complete divisor.

$7 \times 7 = 49$

$7 \times 2 = 14$ annex $1 = 141$

$71 \times 2 = 142$ annex $9 = 1429$

$$\begin{array}{l|l} 51'69'61 & \underline{71} \\ \underline{49} & \\ \ 269 & \\ \ 141 & \\ \ 12861 & \end{array}$$

Next divide 12861 by the complete divisor 1429, or

$$12861 \div 1429 = 9$$

By division it is found that 1429 will go into 12861, 9 times, as indicated above. This is how the next digit, 9, of the root is obtained. We then set down 9 to the right of digits, 7 and 1, which we previously found, thus giving us the total root 719.

$7 \times 7 = 49$

$7 \times 2 = 14$ annex $1 = 141$

$71 \times 2 = 142$ anex $9 = 1429$

$$\begin{array}{l|l} 51'69'61 & \underline{719} \\ \underline{49} & \\ \ 269 & \\ \ \underline{141} & \\ \ 12861 & \end{array}$$

Multiply the complete divisor 1429 by the last root found, or 9.

$1429 \times 9 = 12861$

Write the product 12861 under the remainder 12861.

$7 \times 7 = 49$

$7 \times 2 = 14$ annex $1 = 141$

$71 \times 2 = 142$ annex $9 = 1429$

$$\begin{array}{l|l} 51'69'61 & \underline{719} \\ \underline{49\phantom{'69'61}} & \\ \phantom{0}269 & \\ \phantom{0}141 & \\ \phantom{0}12861 & \\ \phantom{0}\underline{12861} & \end{array}$$

The example finally works out with even values, and we obtain an answer which is a whole number. Since there is no remainder, 719 is the complete root. That is, 719 is the square root of the number 516961.

*Proof:* To prove the answer we must square the complete root 719. If the product of 719 × 719 equals the original number, or 516961, then you are assured that you have worked the problem correctly. The computation below proves that 719 is correct because $719^2$ or 719 × 719 equals 516961.

$$\begin{array}{r} 719 \\ \underline{719} \\ 6471 \\ 719\phantom{0} \\ \underline{5033\phantom{00}} \\ 516961 \end{array}$$

**A Test Exercise in Square Root.** Find $\sqrt{2951314276}$.

The solution of a typical example in square root is given below. The student should work out this exercise independently and check each step with the original explanations for the purpose of testing his ability to perform all the necessary steps correctly.

$$\begin{array}{l|l} 29'51'31'42'76 & \underline{54326} \\ \underline{25\phantom{00}} & \\ \phantom{0}451 & \\ \phantom{0}\underline{416\phantom{0}} & \\ \phantom{00}3531 & \\ \phantom{00}\underline{3249\phantom{0}} & \\ \phantom{000}28242 & \\ \phantom{000}\underline{21724\phantom{0}} & \\ \phantom{0000}651876 & \\ \phantom{0000}\underline{651876} & \end{array}$$

**How to Find the Square Root of an Integral Number.**—To determine the square root of an *integral* number which is not a perfect square, the student should proceed according to the outline given, with exceptions as stated below.

When solving for the square root of an integral number, which is not a perfect square, first determine how many digits, or figures, are required in the answer, and then annex additional ciphers to the right of the number until there are as many decimal periods provided as there will be decimal places (meaning digits) appearing in the root.

Once this has been determined the extracting of the root is done exactly as explained in the section dealing with the square root of a perfect square.

The student must keep in mind that the exact root of a number, which is not a perfect square, cannot be found. An example of this kind is worked out in the paragraphs immediately following.

Example: Find $\sqrt{39}$

The first thing that one must do is to decide upon the number of decimal places (digits) desired in the answer. Suppose you wish to work out the above example to four decimal places, then write down number 39 and annex four decimal periods to the right, consisting of two ciphers each, as shown below:

39.00'00'00'00

The example is now in correct form for solution. The square root is extracted by applying the principles and step-by-step procedure already given in the foregoing parts of this chapter. The first thing to do is to select a figure which when squared will be closest to 39 but not greater than it. This figure is 6, and is written down as the first figure in the root and the rest of the computation is then performed, as follows:

$6^2 = 36$

$6 \times 2 =$ 12 annex 2 makes
122 complete divisor

$62 \times 2 =$ 124 annex 4 makes
1244 complete divisor

$624 \times 2 =$ 1248 annex 4 makes
12484 complete divisor

$6244 \times 2 =$ 12488 annex 9 makes
124889 complete divisor

39.00'00'00'00 | 6.2449 +
36
300
244
5600
4976
62400
49936
1246400
1124001
122399

The decimal point is easily and quickly located in the answer by counting off the same number of decimal places (digits) to the right of the answer, beginning at the decimal point, as there are decimal periods *in the example. Since there were four decimal periods annexed to the right of the decimal point,* following the number 39, then the answer will contain four decimal places as indicated above.

*Proof:* To check the correctness of the foregoing problem we must square the answer, that is, 6.2449 must be multiplied by itself. If you perform this multiplication you will find that the product will not equal the number 39, but will very closely approach 39. This proves that the exact root of an imperfect square cannot be determined.

## GENERAL RULES

The rules just given for extracting square root were applied first to integral numbers which were perfect squares, and second, to integral numbers which were imperfect squares.

The next part of our work involves only *fractional numbers.* Before proceeding further, however, we will state several rules that may be applied to any example in square root involving perfect squares, imperfect squares, or fractional numbers. This is more or less of a review of what has been presented to you thus far. The principles which you have already learned may be applied to examples where the square root of fractional numbers must be found.

### RULE 1

(*A*) **Begin at the decimal point** and divide the number, whose square root is to be found, into periods of two digits each.

When the integral part of the number contains an odd number of digits then only one digit will appear in the left-hand period. This period may contain one or two digits as the case may be. However, in the case of a decimal proceed as explained in the following paragraph (*B*).

(*B*) When the decimal part of the number contains an odd number of digits annex a cipher at the right, so that the last period of the decimal will contain two digits.

*Explanation of Rule* 1.

(*A*) EXAMPLE:

$$\overset{\text{Decimal point}}{\overbrace{\overset{\text{Integral part}}{\overbrace{5\ 5\ 4\ 3\ 2}}\ \overset{\downarrow}{.}\ \overset{\text{Decimal part}}{\overbrace{6\ 4\ 1}}}}$$

Separate, or point off, the number into periods of two digits each, beginning at the decimal point, as follows:

| Point off to left | | Point off to right |
|---|---|---|
| 5′54′32 | . | 64′1 |

(*B*) Since the integral part contains an odd number of digits the extreme left-hand period contains only one digit. As stated before, this period in any case will have one or two digits according to the total number of digits comprising the integral part of the number.

Since the decimal part of the number consists of an odd number of digits, a cipher must be added to complete the last period on the right, thus:

$$\xrightarrow{\qquad\qquad} 5'54'32.64'10_{\nwarrow}$$

One digit in left-hand period of integral number.

Cipher is annexed to complete right-hand period of decimal part of number.

## RULE 2

(*A*) A certain number is selected which when squared will be equal to or less than the first period on the left hand. This number, called a *potential root*, is squared, and the result is placed under the first period.

(*B*) The number, itself (not squared), which was selected according to (*A*) above will be the first digit in the required root.

(*C*) The number, when squared, is subtracted from the first period and the remainder is written down.

(*D*) After you subtract the greatest square from the first period, as suggested in (*C*), bring down the next period and annex it to the remainder found.

*Explanation of Rule* 2:

(*A*) To illustrate Rule 2 consider number 55432.641 whose square root is to be found.

Separate the number into periods of two digits each and annex a cipher to the right-hand period of the decimal part:

$$5'54'32.64'10\,\big|\underline{\qquad}$$

Remember that we are now explaining how to begin your computation and what to do with the first period. Let us try 3 as the first digit in the root. Now square 3, which equals 9. Since 9 is greater than the left-hand period 5, we must try some smaller figure.

This time let us try 1. Now square 1, which equals 1. It is clear that figure 1 is too small.

Try 2. Now square 2, which equals 4. The number 2 is correct, inasmuch as $1^2$ is too small and $3^2$ is too large.

(*B*) Therefore, 2 becomes the first digit of the root, and is written in the bracket as follows:

$$5'54'32.64'10\,\big|\underline{\,2\quad}$$

(*C*) Subtract the square of the root 2, which is 4, from the first period 5 of the number. This gives us a remainder of 1.

$$\begin{array}{lll} 2^2 = 4 & & 5'54'32.64'10\,\big|\underline{\,2\quad} \\ & & 4 \\ & \text{(remainder)} & 1 \end{array}$$

(*D*) Bring down the next period of the number, or 54, and annex it to remainder 1 which makes the total remainder 154.

$$\begin{array}{rl} & 5'54'32.64'10\,\underline{|\,2\phantom{0}} \\ & \underline{4\phantom{00}} \\ \text{(remainder)} & 154 \end{array}$$

### RULE 3

Rule 3 explains how to find the second digit in the root.

(*A*) Now double the root already found, or in other words, multiply the root by 2, and use the product as a trial divisor for the total remainder.

(*B*) Determine how many times the trial divisor, or the product obtained by doubling the root, is contained in the total remainder, disregarding the right-hand figure as we always do in this operation. This will be the next digit of the root, and it should be placed in the bracket to the right of the first digit, and also annexed to the right of the trial divisor to make a complete divisor.

(*C*) Multiply the complete divisor by the last digit placed in the root and write this product under the total remainder.

(*D*) Perform the necessary subtraction and then bring down the next period, annexing it to the remainder just found by subtraction. Now proceed with the problem by repeating this procedure for each digit in the root.

*Explanation of Rule* 3:

(*A*) Double the root just found, and use the product as the trial divisor.

Doubling the root

$2 \times 2 = 4$

$$\begin{array}{l} 5'54'32.64'10\,\underline{|\,2\phantom{0}} \\ \underline{4\phantom{00}} \\ 154 \end{array}$$

*Double this root. The work is done at the left-hand side of the problem.*

Since root 2, when doubled equals 4, then 4 becomes the trial divisor.

(*B*) Find how many times the trial divisor 4 will go into the total remainder 154, disregarding the right-hand figure. This is, in reality, dividing 15 by 4, or $15\cancel{4} \div 4 = 3$.

The result of this last division, or dividing 15 by 4, will give us 3, which becomes the next digit in the root, and by annexing 3 to the trial divisor 4 we obtain the complete divisor, or 43.

Trial divisor.

$2 \times 2 = 4$, annex 3 makes 43

$$\begin{array}{l} 5'54'32.64'10\,\underline{|\,23} \\ \underline{4\phantom{00}} \\ 154 \end{array}$$

**Digit 3 is shown in the foregoing work written to the right of digit 2, which was previously found, and the root thus far is 23.**

**Annexing 3 to the trial divisor makes 43 the complete divisor, is also shown.**

**(*C*) Multiply the complete divisor 43, just found, by the last digit of the root, or 3, and place the product, or 129, under the total remainder 154.**

2 × 2 = 4, annex 3 makes 43

$$\begin{array}{l|l} 5'54'32.64'10 & \underline{23} \\ 4 & \\ 154 & \\ \underline{129} & \end{array}$$

(*D*) The product of 43 × 3, or 129, is subtracted from 154 and the next period 32 of the number is brought down as follows:

$$\begin{array}{l|l} 5'54'32.64'10 & \underline{23} \\ \underline{4} & \\ 154 & \\ \underline{129} & \\ \;\;2532 \leftarrow & \end{array}$$

Period 32 brought down and added to 25 gives 2532, the total remainder.

If we continue our computation to two decimal places according to the same rules we will obtain the following result:

$$\begin{array}{l|l} 5'54'32.64'10 & \underline{235.44 +} \\ \underline{4} & \\ 154 & \\ \underline{129} & \\ \;\;2532 & \\ \;\;\underline{2325} & \\ \;\;\;\;20764 & \\ \;\;\;\;\underline{18816} & \\ \;\;\;\;\;\;194810 & \\ \;\;\;\;\;\;\underline{188336} & \\ \;\;\;\;\;\;\;\;\;\;6474 & \end{array}$$

## RULE 4

After a problem has been worked out to the desired number of decimal places then point off as many (decimal) digits in the root, beginning at the extreme right, as there are decimal periods in the number. There are two decimal periods in the number used for this explanation and, therefore, there will be two decimal places in the answer, as indicated.

*Explanation of Rule* 4:

After completing the foregoing computations and applying the rule about locating the decimal point we find that the square root of 55432.641 is 235.44 +. The + sign indicates that the answer is not complete, but is correct to two decimal places. Also, the + sign signifies that the real answer, which would be obtained if computations were carried beyond this point, would be greater than the answer which we accept as sufficiently accurate.

## RULE 5

The following rule applies only in special cases.

When a trial divisor is too large to go into a remainder, then a cipher should be placed in the root and a cipher also annexed to the trial divisor. Then bring down the next period of the number and carry out the computation in the regular manner.

The following example is given to illustrate how this rule is applied.

EXAMPLE: Find $\sqrt{41653}$

2 × 2 = 4, trial divisor

$$\begin{array}{r|l} 4'16'53 & \underline{2\quad} \\ \underline{4\quad\;\;} & \\ 16\quad\; & \end{array}$$

By inspection it is found that trial divisor 4 cannot be divided into the remainder 16 after we disregard the right-hand figure 6. That is, 4 will not go into 1.

Therefore, place a cipher in the root and also annex a cipher to the trial divisor 4, making a new trial divisor 40. Then bring down the next period of the number 53 and continue with the problem.

2 × 2 = 4, annex 0 makes
40 the new trial divisor.

$$\begin{array}{r|l} 4'16'53 & \underline{204} \\ \underline{4\qquad\;\;} & \\ 1653 & \end{array}$$

Disregarding the right-hand figure in the remainder 1653 gives us 165, and dividing 165 by 40, we obtain 4. Therefore, the next digit in the root is 4.

Annex 4 to the final trial divisor 40, making it 404. Multiply 404 by 4, the last digit of the root, and place the product under the remainder 1653 and subtract.

$2 \times 2 = 4$, annex 0 makes
40 the new trial divisor.

```
404 × 4 = 1616        4'16'53|204 +
                      4
                       1653
                       1616
                         37
```

Thus, we find that the square root of 41,653 is 204 with a remainder.

**How to Find the Square Root of a Decimal.**—To find the square root of a decimal or fraction is just as simple as using integral numbers or whole numbers. Decimals might appear, at first, more difficult to handle because the average student does not ordinarily work with them as frequently as with whole numbers.

(1) EXAMPLE: Find $\sqrt{0.00025}$

A typical example with full explanations is given below. Keep in mind that the first thing to do in any case of this kind is to point off the number into periods of two digits each, beginning at the decimal point, thus:

.00'02'5

After dividing the number into periods, as shown above, we notice that the right-hand period contains but one digit, 5, and therefore a cipher must be annexed to complete this period.

.00'02'50

The computation is now started by selecting a number which is the trial divisor. This number when squared must not be greater than the value of the first period. In this particular instance the first period is 00 and it is quite obvious that there is no number which is equal to zero when squared, hence, a cipher is placed in the bracket as the first digit in the root.

```
0 × 0 = 0             .00'02'50|.0
                        0
```

Bring down the next period, 02, and continue with the example as explained in our instructions which preceded this section. A number is now selected which when squared will not be greater than the value of the second period, or 02. The number which will satisfy this condition is found to be 1, hence 1 is written in the bracket as the next digit in the root.

```
0 × 0 = 0             .00'02'50|.01
1² or 1 × 1 = 1         0
                        02
```

After figure 1 is written in the bracket as just suggested, also place 1 under the remainder 2, and then subtract.

$0 \times 0 = 0$

$1 \times 1 = 1$

$$\begin{array}{r|l} .00'02'50 & \underline{.01} \\ \underline{0\phantom{0}}\phantom{'02'50} & \\ 02\phantom{'50} & \\ \underline{1}\phantom{'50} & \\ 1\phantom{'50} & \end{array}$$

This leaves a remainder of 1 to which the next period 50 is annexed. The total remainder is now 150.

$0 \times 0 = 0$

$1 \times 1 = 1$

$$\begin{array}{r|l} .00'02'50 & \underline{.01} \\ \underline{0\phantom{0}}\phantom{'02'50} & \\ 02\phantom{'50} & \\ \underline{1\phantom{50}} & \\ 150 & \end{array}$$

Multiply the root 1 (which is written in the bracket) by 2 in order to obtain a trial divisor and then determine the number of times this trial divisor, or 2, is contained into 150, disregarding the right-hand digit in 150. This means, of course, that 15 is to be divided by 2, which equals 7. This figure just obtained, or 7, is called the potential root. We now annex 7 to the trial divisor 2, giving us 27, and by multiplying 27 by the potential root 7 we obtain the figure 189, thus

$27 \times 7 = 189$

Since figure 189 is larger than the total remainder 150 it is very evident that we cannot use 7 as the next digit in the root. Therefore, we must try a number which is less than 7. Let us try 6. The figure 6 now becomes the potential root.

The figure 6 or potential root, is annexed to the trial divisor 2 and we have 26. Multiplying the potential root 6 by 26 equals 156. We cannot use 6 as the next digit in the root since 156 is greater than 150, and therefore, we must try a smaller figure. Let us try 5 this time.

Apply the same line of reasoning in regard to the use of 5 as we did in the case of the other trial divisors, 7 and 6, which could not be used.

Trial divisor 2 with 5 annexed equals 25. Potential root 5 multiplied by 25 equals 125. Since 125 is not greater than 150, then it is evident that 5 can be applied as the next digit in the root.

Therefore, write 5 in the bracket as the next digit in the root; then multiply the final divisor, or 25, by the root 5, and place the total, or 125, under 150 as follows:

$0 \times 0 = 0$

$1 \times 1 = 1$

$1 \times 2 = 2$ annex 5 makes
25 complete divisor

$25 \times 5 = 125.$

.00′02′50 | .015 +
0
02
1
150
125
25

If the answer is sufficiently accurate, for the purpose at hand, when the root is carried out to three decimal places, then our work is completed. But suppose an answer containing four decimal places is required; then we must go through one more computation according to the principles already outlined.

To give you additional practice in working out examples of this kind let us carry out the answer to one more decimal place. To do this annex a period consisting of two ciphers to the right of the last period 50 and continue with the work.

$0 \times 0 = 0$

$1 \times 1 = 1$

$1 \times 2 = 2$ annex 5 makes
25

$25 \times 5 = 125$

$15 \times 2 = 30$ annex 8 makes
308 complete divisor

$308 \times 8 = 2464$

.00′02′50′00 | .0158 +
0
02
1
150
125
2500
2464
36

Hence, we have found that the square root of 0.00025 is 0.0158 +. This answer is correct to four decimal places.

(2) **Example:** Given the number .0005, find its square root. The answer should contain four decimal places.

The solution to this example is given below without all the work being shown. This is done in order to give you an opportunity to work the same example step by step, showing *all* the work, and afterward to check your computation.

.00′05′00′00 | .0223 + *Ans.*
0
05
4
100
84
1600
1329
271

### How to Find the Square Root of a Fraction.

(1) Example: Find $\sqrt{\frac{25}{81}}$.

In this problem it is seen that both the numerator, or 25, and denominator, or 81, are perfect squares. Therefore, to work out this problem we simply take the square root of the numerator and denominator separately and then remove the radical sign as follows:

The square root of 25 is 5; and that of 81 is 9. Hence, $\sqrt{\frac{25}{81}} = \frac{5}{9}$.

Simple examples like the one given above can be solved merely by inspection. However, this cannot be done when the numerator and denominator are not perfect squares. In an example of the latter kind you should first reduce the fraction to a decimal and then proceed to find the square root of the decimal.

(2) Example: Find $\sqrt{\frac{2}{7}}$.

First reduce the fraction $\frac{2}{7}$ to a decimal by dividing 2 by 7. Thus, we find that $\frac{2}{7} = 0.28571 +$.

The next step is to find the square root of 0.28571. The same step-by-step procedure is followed in all cases where a decimal is involved in square root.

After working out this problem you should obtain 0.5345 for the answer, which is not fully complete since there is a remainder, but in the majority of cases a decimal carried out to three or four places is accepted as sufficiently accurate for all practical purposes. In expressing this result we would say that 0.5345 is the square root of $\frac{2}{7}$ correct to four decimal places.

## PROBLEMS ON CHAPTER IX

**1.** $\dfrac{4785.85}{15.3} = ?$

**2.** $\frac{4}{5} + \frac{5}{6} + \frac{5}{8} = ?$

**3.** Reduce the fraction $\frac{18}{35}$ to a decimal.

**4.** $2.105 \times 0.245 = ?$

**5.** Multiply $\frac{3}{8}$ by $\frac{13}{16}$ and reduce the product found to a decimal.

**6.** $\frac{14}{17} \div \frac{28}{32} = ?$

**7.** What is the square root of $\frac{144}{255}$?

**8.** What is the square root of .0065536?

**9.** What is the square root of 466569?

**10.** What is the square root of 96.6289?

**11.** What is the square root of $8\frac{2}{5}$?

**12.** What is the square root of 1.3765?

**13.** Divide $\frac{28}{35}$ by $\frac{4}{7}$ and then find the square root of the answer to this division.

**14.** Multiply 1.01 by 70.007 and then find the square root of the answer to this multiplication.

# APPENDIX

## MELTING POINTS OF ELEMENTS

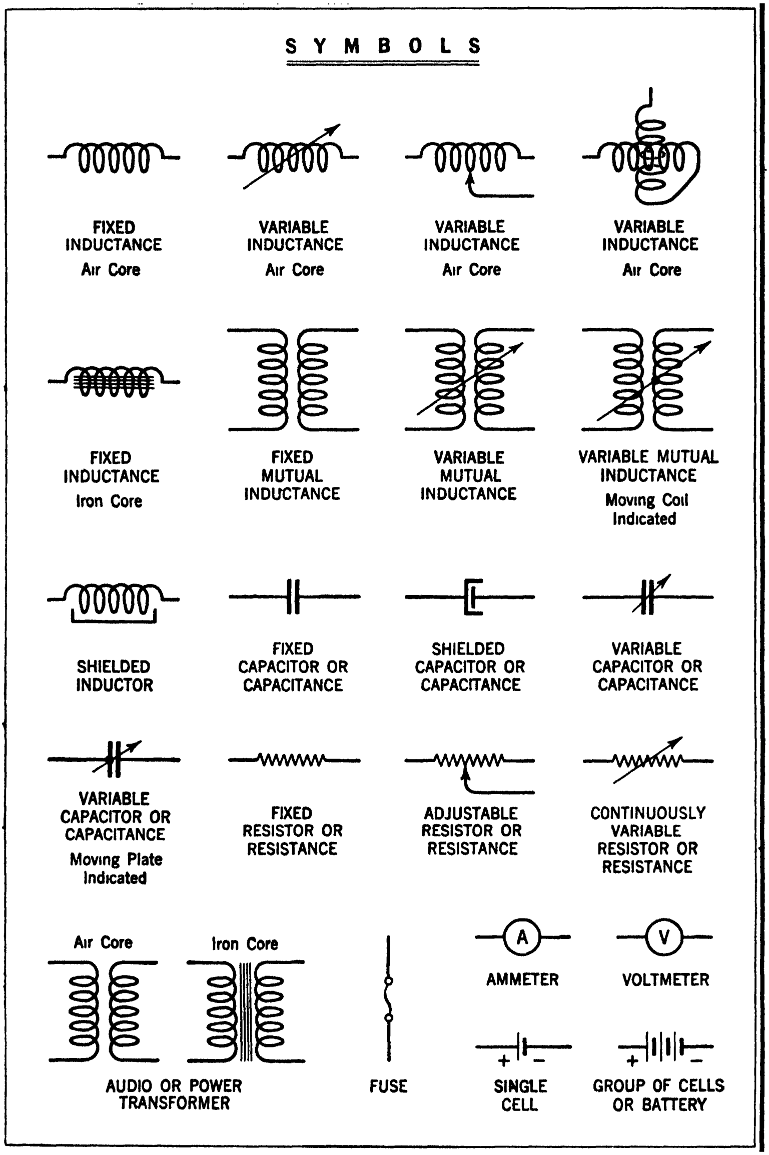
(U. S. Bureau of Standards)

| ELEMENT | Degrees Fahrenheit | Degrees Centigrade | ELEMENT | Degrees Fahrenheit | Degrees Centigrade |
|---|---|---|---|---|---|
| Aluminum...... | 1220 | 660 | Molybdenum.... | 4748 | 2620 |
| Antimony...... | 1166.0 | 630.0 | Nickel......... | 2646 | 1452 |
| Bismuth......... | 520 | 271 | Nitrogen........ | −346 | −210 |
| Cadmium...... | 609.6 | 320.9 | Oxygen......... | −360 | −218 |
| Chromium...... | 2939 | 1615 | Palladium...... | 2831 | 1555 |
| Cobalt.......... | 2696 | 1480 | Platinum....... | 3191 | 1755 |
| Copper.......... | 1981.4 | 1083.0 | Potassium....... | 144.1 | 62 3 |
| Gold............ | 1945.5 | 1063.0 | Silver.......... | 1760 9 | 960 5 |
| Hydrogen...... | −434 | −259 | Sodium........ | 207.5 | 97 5 |
| Iodine......... | 236.3 | 113.5 | Sulphur........ | 246.6 | 119.2 |
| Iridium........ | 4260 | 2350 | Tantalum...... | 5162 | 2850 |
| Iron........... | 2786 | 1530 | Tin........... | 449.4 | 231.9 |
| Lead............ | 621.3 | 327.4 | Titanium........ | 3272 | 1800 |
| Magnesium..... | 1204 | 651 | Tungsten....... | 6098 | 3370 |
| Manganese...... | 2300 | 1260 | Vanadium...... | 3110 | 1710 |
| Mercury..... . | −38 0 | −38.9 | Zinc......... . | 786.9 | 419 4 |

## USEFUL CONVERSION RATIOS

| Multiply | by | to obtain |
|---|---|---|
| Diameter Circle | 3.1416 | Circumference Circle |
| Diameter Circle | 0.886 | Side Equal Square |
| U. S. Gallons | 0.8333 | Imperial Gallons |
| U. S. Gallons | 0.1337 | Cubic Feet |
| Inches Mercury | 0.4912 | Pounds per Square Inch |
| Feet of Water | 0.4335 | Pounds per Square Inch |
| Cubic Feet | 62.4 | Pounds of Water |
| U. S. Gallons | 8.343 | Pounds of Water |
| U. S. Gallons | 3.785 | Liters |
| Knots | 1.152 | Miles |
| Inches | 2.540 | Centimeters |
| Yards | 0.9144 | Meters |
| Miles | 1.609 | Kilometers |
| Cubic Inches | 16.39 | Cubic Centimeters |
| Ounces | 28.35 | Grams |
| Pounds | 0.4536 | Kilograms |

## SYMBOLS


FIXED INDUCTANCE
Air Core
VARIABLE INDUCTANCE
Air Core
VARIABLE INDUCTANCE
Air Core
VARIABLE INDUCTANCE
Air Core
FIXED INDUCTANCE
Iron Core
FIXED MUTUAL INDUCTANCE
VARIABLE MUTUAL INDUCTANCE
VARIABLE MUTUAL INDUCTANCE
Moving Coil Indicated
SHIELDED INDUCTOR
FIXED CAPACITOR OR CAPACITANCE
SHIELDED CAPACITOR OR CAPACITANCE
VARIABLE CAPACITOR OR CAPACITANCE
VARIABLE CAPACITOR OR CAPACITANCE
Moving Plate Indicated
FIXED RESISTOR OR RESISTANCE
ADJUSTABLE RESISTOR OR RESISTANCE
CONTINUOUSLY VARIABLE RESISTOR OR RESISTANCE
Air Core
Iron Core
AUDIO OR POWER TRANSFORMER
FUSE
A
AMMETER
V
VOLTMETER
+
−
SINGLE CELL
+
−
GROUP OF CELLS OR BATTERY

## METRIC EQUIVALENTS

### LENGTH

| | |
|---|---|
| Centimeter = .3937 Inch | Inch = 2.54 Centimeters |
| Meter = 3.28 Feet | Foot = .305 Meter |
| Meter = 1.094 Yards | Yard = .914 Meter |
| Kilometer = .621 Mile | Mile = 1.61 Kilometers |

### AREA

| | |
|---|---|
| Square Centimeter = 0.1550 Square inch | Square inch = 6.452 Sq. Cm. |
| Square Meter = 10.764 Square feet | Square foot = .0929 Sq. M. |
| Square Meter = 1.196 Square yards | Square yard = .836 Sq. M. |
| Hectare = 2.47 Acres | Acre = .405 Hectare |
| Square Kilometer = .386 Square mile | Square mile = 2.59 Sq. Kilom. |

### VOLUME

| | |
|---|---|
| Cubic Centimeter = .061 Cubic inch | Cubic inch = 16.4 Cubic Cm. |
| Cubic Meter = 35.31 Cubic feet | Cubic foot = .028 Cubic M. |
| Cubic Meter = 1.308 Cubic yards | Cubic yard = .765 Cubic M. |

### CAPACITY

| | |
|---|---|
| Litre = .0353 Cubic foot | Cubic foot = 28.32 Litres |
| Litre = .2642 Gal. (U. S.) | Gallon = 3.785 Litres |
| Litre = 61.023 Cubic inches | Cubic inch = .0164 Litre |

Litre = 2.202 lb. of fresh water at 62° F.

### WEIGHT

| | |
|---|---|
| Gram = 15.423 Grains | Ounce = 28.35 Grams |
| Gram = .0353 Ounce | Pound = .454 Kilogram |
| Kilogram = 2.205 Pounds | Ton (Short) = 907.03 Kilograms |
| Kilogram = .0011 Ton (Short) | Ton (Short) = .907 Met. Ton |
| Metric Ton = 1.1025 Tons (Short) | Ton (Short) = 2,000 Pounds |
| Grain = .0684 Gram | |

### PRESSURE

Kilograms per square centimeter = 14.225 pounds per square inch
Pounds per square inch = .0703 kilogram per square centimeter
Kilograms per square meter = .205 pound per square foot
Pounds per square foot = 4.88 kilograms per square meter
Kilograms per square centimeter = .968 atmosphere
Atmosphere = 1.033 kilograms per square centimeter

### MISCELLANEOUS

Kilogrammeter = 7.233 foot-pounds
Foot-pound = .1383 kilogrammeter
Metric horse-power = .986 horse-power
Horse-power = 1.014 metric horse-power
Litre per second = 2.12 cubic feet per minute
Litre per second = 15.85 U. S. gallons per minute

## METRIC AND DECIMAL EQUIVALENTS OF COMMON FRACTIONS

| Fractions of an inch | Decimals of an inch | Milli-meters | Fractions of an inch | Decimals of an inch | Milli-meters |
|---|---|---|---|---|---|
| 1/64 | .0156 | 0.397 | 33/64 | .5156 | 13.097 |
| 1/32 | 0313 | 0.794 | 17/32 | .5313 | 13.494 |
| 3/64 | 0469 | 1.191 | 35/64 | .5469 | 13.891 |
| 1/16 | .0625 | 1.588 | 9/16 | .5625 | 14.287 |
| 5/64 | .0781 | 1.985 | 37/64 | .5781 | 14.684 |
| 3/32 | .0938 | 2.381 | 19/32 | .5938 | 15.081 |
| 7/64 | .1094 | 2.778 | 39/64 | .6094 | 15.478 |
| 1/8 | .1250 | 3.175 | 5/8 | .6250 | 15.875 |
| 9/64 | .1406 | 3.572 | 41/64 | .6406 | 16.272 |
| 5/32 | .1563 | 3.969 | 21/32 | .6563 | 16.688 |
| 11/64 | 1719 | 4.366 | 43/64 | .6719 | 17.085 |
| 3/16 | .1875 | 4.762 | 11/16 | .6875 | 17.462 |
| 13/64 | .2031 | 5.159 | 45/64 | .7031 | 17.859 |
| 7/32 | .2188 | 5.556 | 23/32 | .7188 | 18.256 |
| 15/64 | .2344 | 5.953 | 47/64 | .7344 | 18.653 |
| 1/4 | .2500 | 6.350 | 3/4 | .7500 | 19.050 |
| 17/64 | .2656 | 6.747 | 49/64 | .7656 | 19 447 |
| 9/32 | 2813 | 7.144 | 25/32 | .7813 | 19 843 |
| 19/64 | 2969 | 7.541 | 51/64 | .7969 | 20.240 |
| 5/16 | .3135 | 7.937 | 13/16 | .8125 | 20.637 |
| 21/64 | .3281 | 8.334 | 53/64 | .8281 | 21.034 |
| 11/32 | .3438 | 8.731 | 27/32 | .8438 | 21.430 |
| 23/64 | .3594 | 9.128 | 55/64 | .8594 | 21.827 |
| 3/8 | .3750 | 9.525 | 7/8 | .8750 | 22.224 |
| 25/64 | 3906 | 9.922 | 57/64 | .8906 | 22.621 |
| 13/32 | .4063 | 10.319 | 29/32 | .9063 | 23.018 |
| 27/64 | .4219 | 10.716 | 59/64 | .9219 | 23.415 |
| 7/16 | .4375 | 11.12 | 15/16 | .9375 | 23.812 |
| 29/64 | .4531 | 11.509 | 61/64 | .9531 | 24.209 |
| 15/32 | .4688 | 11.906 | 31/32 | .9688 | 24.606 |
| 31/64 | .4844 | 12.303 | 63/64 | .9844 | 25.003 |
| 1/2 | .5000 | 12 700 |  | 1 0000 | 25.400 |

## EQUIVALENTS OF ELECTRICAL UNITS

1 kilowatt = 1000 watts
1 kilowatt = 1.34 H. P.
1 kilowatt = 44,257 foot-pounds per minute
1 kilowatt = 56.87 B.T.U. per minute
1 horse-power = 746 watts
1 horse-power = 33,000 foot-pounds per minute
1 horse-power = 42.41 B.T.U. per minute
1 B.T.U. (British thermal unit) = 778 foot-pounds
1 B.t.u. = 0.2930 watt-hour
1 joule = 1 watt-second

## ALLOWABLE CARRYING CAPACITIES OF COPPER WIRE AND CABLE

(Regulations of the National Board of Fire Underwriters)

| No. AWG | Circular Mils | Amperes | | Circular Mils | Amperes | |
|---|---|---|---|---|---|---|
| | | Rubber Insulation | Other Insulation | | Rubber Insulation | Other Insulation |
| 18 | 1,624 | 3 | 5 | 250,000 | 250 | 350 |
| 16 | 2,583 | 6 | 10 | 300,000 | 275 | 400 |
| 14 | 4,107 | 15 | 20 | 350,000 | 300 | 450 |
| 12 | 6,530 | 20 | 25 | 400,000 | 325 | 500 |
| 10 | 10,380 | 25 | 30 | 450,000 | 362 | 550 |
| 8 | 16,510 | 35 | 50 | 500,000 | 400 | 600 |
| 6 | 26,250 | 50 | 70 | 600,000 | 450 | 680 |
| 4 | 41,740 | 70 | 90 | 700,000 | 500 | 760 |
| 2 | 66,370 | 90 | 125 | 800,000 | 550 | 840 |
| 1 | 83,690 | 100 | 150 | 1,000,000 | 650 | 1000 |
| 0 | 105,500 | 125 | 200 | 1,250,000 | 750 | 1180 |
| 00 | 133,100 | 150 | 225 | 1,500,000 | 850 | 1360 |
| 000 | 167,800 | 175 | 275 | 1,750,000 | 950 | 1520 |
| 0000 | 211,600 | 225 | 325 | 2,000,000 | 1050 | 1670 |

## TEMPERATURE CORRECTIONS FOR COPPER WIRE

(Based on A.I.E.E. Standards)

TEMPERATURE COEFFICIENT OF RESISTANCE. At a temperature of 25° C. the "constant mass" temperature coefficient of resistance of standard annealed copper, measured between potential points rigidly fixed to the wire is 0.00385 or 1/259.5 per Centigrade degree.

Resistance values of copper wire given in table on page 238 in this appendix may be corrected for any temperature by means of the formula given below.

### CORRECTIONS FOR CHANGE IN TEMPERATURE

$Rt = R_{25}\,[1 + 0.00385\,(t - 25)]$, where
$Rt$ = the resistance in ohms at a temperature, $t$
$R_{25}$ = the resistance in ohms at 25° C.
$t$ = the temperature of wire in degrees, Centigrade.

## DIAMETER, WEIGHTS AND RESISTANCE OF COPPER WIRE

| No AWG | Diameter, Mils | Area, Circular Mils | Weight, Bare Wire | | Resistance at 25° C (77° F ) | | |
|---|---|---|---|---|---|---|---|
| | | | Pounds per 1000 Ft | Pounds per Mile | Ohms per 1000 Ft | Ohms per Mile | Feet per Ohm |
| 0000 | 460 | 211,600 | 641 | 3385 | 0 0499 | 0 2638 | 20,040 |
| 000 | 410 | 167,800 | 508 | 2683 | 0 0630 | 0 3325 | 15,870 |
| 00 | 364 8 | 133,100 | 403 | 2126 | 0 0794 | 0 419 | 12,590 |
| 0 | 324 9 | 105,500 | 319 5 | 1687 | 0 1003 | 0 529 | 9,980 |
| 1 | 289 3 | 83,700 | 253 3 | 1337 | 0 1262 | 0 666 | 7,930 |
| 2 | 257 6 | 66,400 | 200 9 | 1061 | 0 1591 | 0 840 | 6,290 |
| 3 | 229 4 | 52,600 | 159 3 | 841 | 0 2008 | 1 062 | 4,980 |
| 4 | 204 3 | 41,700 | 126 4 | 668 | 0 2533 | 1 338 | 3,950 |
| 5 | 181 9 | 33,100 | 100 2 | 529 | 0 3193 | 1 685 | 3,134 |
| 6 | 162 0 | 26,250 | 79 5 | 419 | 0 403 | 2 127 | 2,485 |
| 7 | 144 3 | 20,820 | 63 0 | 332 6 | 0 507 | 2 682 | 1,971 |
| 8 | 128 5 | 16,510 | 50 0 | 264 0 | 0 640 | 3 382 | 1,562 |
| 9 | 114 4 | 13,090 | 39 63 | 208 3 | 0 807 | 4 26 | 1,238 |
| 10 | 101 9 | 10,380 | 31 43 | 165 9 | 1 017 | 5 37 | 983 |
| 11 | 90 7 | 8,230 | 24 92 | 131 6 | 1 284 | 6 78 | 779 |
| 12 | 80 8 | 6,530 | 19 77 | 104 3 | 1 618 | 8 55 | 618 |
| 13 | 72 0 | 5,180 | 15 68 | 82 8 | 2 040 | 10 77 | 490 |
| 14 | 64 1 | 4,110 | 12 43 | 65 6 | 2 575 | 13 60 | 388 2 |
| 15 | 57 1 | 3,257 | 9 86 | 52 1 | 3 244 | 17 13 | 308 4 |
| 16 | 50 8 | 2,583 | 7 82 | 41 3 | 4 09 | 21 62 | 244 3 |
| 17 | 45 3 | 2,048 | 6 20 | 32 73 | 5 16 | 27 24 | 193 9 |
| 18 | 40 3 | 1,624 | 4 92 | 26 00 | 6 51 | 34 34 | 153 7 |
| 19 | 35 89 | 1,288 | 3 899 | 20 57 | 8 20 | 43 3 | 121 9 |
| 20 | 31 96 | 1,022 | 3 092 | 16 33 | 10 34 | 54 6 | 96 6 |
| 21 | 28 46 | 810 | 2 452 | 12 93 | 13 04 | 68 9 | 76 6 |
| 22 | 25 35 | 642 | 1 945 | 10 27 | 16 44 | 86 9 | 60 8 |
| 23 | 22 57 | 509 | 1 542 | 8 14 | 20 75 | 109 5 | 48 2 |
| 24 | 20 10 | 404 | 1 223 | 6 46 | 26 15 | 138 1 | 38 25 |
| 25 | 17 90 | 320 4 | 0 970 | 5 12 | 33 00 | 174 3 | 30 30 |
| 26 | 15 94 | 254 1 | 0 769 | 4 06 | 41 6 | 219 5 | 24 04 |
| 27 | 14 20 | 201 5 | 0 610 | 3 220 | 52 4 | 276 8 | 19 07 |
| 28 | 12 64 | 159 8 | 0 484 | 2 556 | 66 1 | 349 2 | 15 13 |

## SPECIFIC HEATS AND MELTING-POINTS

| | Average Specific Heat | Average Watt-hours to Heat 1 Lb 1 Deg C | Average Watt-hours to Heat 1 Lb 1 Deg F | Heat of Fusion Watt-hours per Lb | Melting-Point Deg C | Lb per Cubic Foot |
|---|---|---|---|---|---|---|
| Air (at 68° F ) | 0 237 | 0 125 | 0 0695 | | | 0 08074 |
| Aluminum | 0 22 | 0 116 | 0 065 | | 660 | 160 |
| Brass | 0 091 | 0 048 | 0 0266 | | 850–1200 | 511–536 |
| Carbon | 0 204 | 0 107 | 0 0595 | | | |
| Copper | 0 094 | 0 0495 | 0 0275 | 22 8 | 1083 | 555 |
| Graphite | 0 20 | 0 105 | 0 0583 | | | 120–140 |
| Iron, gray | 0 11 | 0 058 | 0 0322 | 12 2 | 1200 | 450 |
| cast | 0 22 | 0 116 | 0 0645 | | | |
| Lead, solid | 0 031 | 0 0163 | 0 00905 | 3 1 | 327 4 | 710 |
| Lead, fluid | 0 0471 | 0 0248 | 0 0138 | | | |
| Nickel | 0 11 | 0 058 | 0 0322 | 2 45 | 1452 | 517–573 |
| Paraffin, | 0 62 | 0 326 | 0 181 | | 38–56 | 54 25–56 75 |
| solid | 0 69 | 0 363 | 0 202 | | | |
| Paraffin, fluid | 0 71 | 0 374 | 0 208 | 18 5 | | 52 4–57 |
| Pitch | | | | | | 67 |
| Rosin, solid | | | | | | 67 |
| Solder (1 tin, 1 lead) | | | | 5 30 | 205 | 555 |
| Solder (2 tin, 1 lead) | | | | 9 0 | 185 | 520 |
| Tallow | | | | | 33 3 | 57–60 5 |
| Tar | | | | | | 62–63 4 |
| Tin, solid | 0 056 | 0 0295 | 0 0164 | 7 4 | 232 | 455 |
| Tin, fluid | 0 064 | 0 0337 | 0 0187 | | | 436 |
| *Type metal | 0 039 | 0 0206 | 0 0114 | | | 260 |
| Water (68° F ) | 1 0 | 0 527 | 0 293 | 42 3 | 0 | 62 42 |
| Wax, bees | | | | 22 4 | 61–68 | 60–61 |
| Zinc, cast | 0 093 | 0 049 | 0 0272 | 14 8 | 419 4 | 439–446 5 |
| | 0 12 | 0 063 | 0 035 | | | |
| Zinc, fluid | | | | | | 404 |

* 80 parts lead 20 parts antimony

## CENTIGRADE AND FAHRENHEIT TEMPERATURE SCALES

| Centigrade | Fahrenheit | Centigrade | Fahrenheit | Centigrade | Fahrenheit | Centigrade | Fahrenheit |
|---|---|---|---|---|---|---|---|
| 0 | 32 | 30 | 86 | 50 | 122 | 80 | 176 |
| 5 | 41 | 35 | 95 | 55 | 131 | 85 | 185 |
| 10 | 50 | 38 | 100 4 | 60 | 140 | 90 | 194 |
| 15 | 59 | 40 | 104 | 65 | 149 | 95 | 203 |
| 20 | 68 | 42 | 107 6 | 70 | 158 | 100 | 212 |
| 25 | 77 | 45 | 113 | 75 | 167 | | |

Temp C = (Temp F ) − 32

Temp F = (Temp C ) + 32

## WEIGHT OF MATERIALS

| Materials | Pounds per Cubic Foot | Specific gravity Water = 1 |
|---|---|---|
| Aluminum, cast | 160 | 2.56 |
| Aluminum, wrought | 169.17 | 2.71 |
| Antimony | 415.94 | 6.62 |
| Asbestos Board | 74.91 | 1.2 |
| Balsa | 7.5 | .12 |
| Benzene | 53.1 | .85 |
| Bismuth | 614.9 | 9.85 |
| Brass, cast | 505 | 8.10 |
| Brass, wire | 533 | 8.548 |
| Bronze | 544 | 8.73 |
| Constantan | 555.58 | 8.9 |
| Copper | 558.09 | 8.94 |
| Copper, cast | 530.63 | 8.5 |
| Cork | 10.15 | .16–.24 |
| Ebonite | 71.71 | 1.15 |
| Ether, Sulphuric | 44.9 | .713 |
| German Silver | 555.58 | 8.9 |
| Glass | 149–187 | 2.4–3 |
| Gold | 1206.09 | 19.32 |
| Granite | 156–187 | 2.5–3 |
| Iron, cast | 443.21 | 7.1 |
| Iron, wrought | 486.93 | 7.8 |
| Lead, wire | 708.65 | 11.35 |
| Magnalium | 124.85 | 2 |
| Mercury fluid | 846.51 | 13.56 |
| Molybdenum | 536 | 8.6 |
| Naphtha | 53.1 | .85 |
| Nickel, cast | 555.58 | 8.9 |
| Nitric Acid | 76.2 | 1.22 |
| Oak | 49.94 | .80 |
| Oil, linseed | 58.31 | .935 |
| Oil, turpentine | 54.3 | .87 |
| Paper | 43–68 | .7–1.1 |
| Petroleum | 54.9 | .88 |
| Phosphor Bronze | 549.35 | 8.8 |
| Platinum | 1342 | 21.5 |
| Pure Water | 62.425 | 1.000 |
| Sandstone | 143.58 | 2.3 |
| Silver | 655 | 10.5 |
| Steel | 489.6 | 7.8 |
| Sulphuric Acid (conc.) | 114.9 | 1.84 |
| Tin | 454.60 | 7.3 |
| Tungsten | 1193 | 19.4 |
| Walnut | 43.69 | .7 |
| White Pine (seas.) | 31.21 | .5 |
| Zinc, sheet | 449 | 7.2 |

## WINDING TURNS PER LINEAR INCH

| B & S Gauge No. | D.C.C. | S.C.C. | Enamel |
|---|---|---|---|
| 6 | 5.44 | 5.60 | |
| 7 | 6.08 | 6.23 | |
| 8 | 6.80 | 6.94 | |
| 9 | 7.64 | 7.68 | |
| 10 | 8.51 | 8.55 | |
| 11 | 9.58 | 9.60 | |
| 12 | 10.62 | 10.80 | |
| 13 | 11.88 | 12.06 | |
| 14 | 13.10 | 13.45 | 14.00 |
| 15 | 14.68 | 14.90 | 16.00 |
| 16 | 16.40 | 17.20 | 18.00 |
| 17 | 18.10 | 18.80 | 21.00 |
| 18 | 20.00 | 21.00 | 23.00 |
| 19 | 21.83 | 23.60 | 27.00 |
| 20 | 23.91 | 26.40 | 29.00 |
| 21 | 26.20 | 29.70 | 32.00 |
| 22 | 28.58 | 32.00 | 36.00 |
| 23 | 31.12 | 34.30 | 40.00 |
| 24 | 33.60 | 37.70 | 45.00 |
| 25 | 36.20 | 41.50 | 50.00 |
| 26 | 39.90 | 45.30 | 57.00 |
| 27 | 42.60 | 49 40 | 64.00 |
| 28 | 45.50 | 54.00 | 71.00 |
| 29 | 48.00 | 58.80 | 81.00 |
| 30 | 51.10 | 64.40 | 88.00 |
| 31 | 56.80 | 69.00 | 104.00 |
| 32 | 60.20 | 75.00 | 120.00 |
| 33 | 64.30 | 81.00 | 130 00 |
| 34 | 68.60 | 87.60 | 140.00 |
| 35 | 73.00 | 94.20 | 160.00 |
| 36 | 78.50 | 101.00 | 190.00 |
| 37 | 84.00 | 108 00 | 195.00 |
| 38 | 89.10 | 115.00 | 205.00 |
| 39 | 95.00 | 122.50 | 215.00 |
| 40 | 102.50 | 130.00 | 230.00 |
| 41 | 112.00 | 153.00 | 240.00 |
| 42 | 124.00 | 168.00 | 253.00 |
| 43 | 140.00 | 192.00 | 265.00 |
| 44 | 153.00 | 210.00 | 275.00 |

## CONVERSION

### FACTORS FOR CONVERSION, ALPHABETICALLY ARRANGED

| Multiply | By | To Get |
|---|---|---|
| Amperes | 1,000,000,000,000 | Micromicroamperes |
| Amperes | 1,000,000 | Microamperes |
| Amperes | 1,000 | Milliamperes |
| Cycles | .000,001 | Megacycles |
| Cycles | .001 | Kilocycles |
| Farads | 1,000,000,000,000 | Micromicrofarads |
| Farads | 1,000,000 | Microfarads |
| Farads | 1,000 | Millifarads |
| Henrys | 1,000,000 | Microhenrys |
| Henrys | 1,000 | Millihenrys |
| Kilocycles | 1,000 | Cycles |
| Kilovolts | 1,000 | Volts |
| Kilowatts | 1,000 | Watts |
| Megacycles | 1,000,000 | Cycles |
| Mhos | 1,000,000 | Micromhos |
| Mhos | 1,000 | Millimhos |
| Microamperes | .000,001 | Amperes |
| Microfarads | .000,001 | Farads |
| Microhenrys | .000,001 | Henrys |
| Micromhos | .000,001 | Mhos |
| Micro-ohms | .000,001 | Ohms |
| Microvolts | .000,001 | Volts |
| Microwatts | .000,001 | Watts |
| Micromicrofarads | .000,000,000,001 | Farads |
| Micromicro-ohms | .000,000,000,001 | Ohms |
| Milliamperes | .001 | Amperes |
| Millihenrys | .001 | Henrys |
| Millimhos | .001 | Mhos |
| Milliohms | .001 | Ohms |
| Millivolts | .001 | Volts |
| Milliwatts | .001 | Watts |
| Ohms | 1,000,000,000,000 | Micromicro-ohms |
| Ohms | 1,000,000,000 | Micro-ohms |
| Ohms | 1,000 | Milliohms |
| Volts | 1,000,000 | Microvolts |
| Volts | 1,000 | Millivolts |
| Watts | 1,000,000 | Microwatts |
| Watts | 1,000 | Milliwatts |
| Watts | .001 | Kilowatts |

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